PB-240 573

AIR POLLUTION: CONTROL TECHNIQUES FOR PARTICULATE AIR POLLUTANTS

NATO Committee on the Challenges of Modern Society

Prepared for:

Environmental Protection Agency
Research Triangle Institute

October 1973

DISTRIBUTED BY:

NTIS
National Technical Information Service
U. S. DEPARTMENT OF COMMERCE

BIBLIOGRAPHIC DATA SHEET

1. Report No.

2\.

PB 240 573

4. Title and Subtitle

Air Pollution, Control technques for particulate air pollutants

5. Report Date

October 1973

6\.

7. Author(s)

8. Performing Organization Rept. No. 13

9. Performing Organization Name and Address

NATO Committee on the Challenges of Modern Society, 1110 Bruxelles, Brussels, Belgium

10. Project/Task/Work Unit No.

11. Contract/Grant No.

12. Sponsoring Organization Name and Address

Office of Air and Waste Management, Environmental Protection Agency, Washington, D. C. 20460

13. Type of Report & Period Covered

14\.

15. Supplementary Notes

16. Abstracts

17. Key Words and Document Analysis. 17a. Descriptors

air pollution
particulate sources
control techniques

17b. Identifiers/Open-Ended Terms

Reproduced by
NATIONAL TECHNICAL INFORMATION SERVICE
US Department of Commerce
Springfield, VA. 22151

PRICES SUBJECT TO CHANGE

17c. COSATI Field/Group

18. Availability Statement

19. Security Class (This Report) UNCLASSIFIED

20. Security Class (This Page UNCLASSIFIED

21. No. of Pages 220

22. Price PC/MF 7.25/2.25

FORM NTIS-35 (REV. 10-73) ENDORSED BY ANSI AND UNESCO. THIS FORM MAY BE REPRODUCED USCOMM-DC 8265-P74

CONTROL TECHNIQUES
FOR
PARTICULATE AIR POLLUTANTS

RTI

PREPARED FOR
THE COMMITTEE ON THE CHALLENGES
OF MODERN SOCIETY

NATO

October, 1973

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*Also available in French
**French version available by Spring 1974

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FOREWORD

This document is a compilation of information on methods for the control of particulate air pollutants that was assembled by the Expert Panel for Air Pollution Control Technology, The Committee on the Challenges of Modern Society, NATO, for distribution to the member countries.

The Chairman of the Expert Panel wishes to acknowledge the efforts of scientists from the pilot countries, scientists from observer countries, and the many other persons who assisted in the preparation of this document and the four companion volumes: *Control Techniques for Carbon Monoxide Emissions from Stationary Sources*, *Control Techniques for Hydrocarbon and Organic Solvent Emissions from Stationary Sources*, *Control Techniques for Sulfur Oxide Air Pollutants*, and *Control Techniques for Nitrogen Oxide Emissions from Stationary Sources*.

Thanks are due the Environmental Protection Agency of the United States for permission to use their document, *Control Techniques for Particulate Air Pollutants*, which was published in 1969, as a basis for this effort.

Major contributions were made by a team of scientists from the Federal Republic of Germany under the direction of Dr. Dieter Hartmann. These contributions were invaluable to the success of the effort.

Recognition should also be given to the team from the Research Triangle Institute, Research Triangle Park, North Carolina, USA, for their efforts in literature searches, writing, and editorial work.

Lastly, acknowledgment should be given to those secretaries and other support personnel who have made the panel effort possible.

John K. Burchard, Ph.D.
Panel Chairman

TABLE OF CONTENTS

SUMMARY iii
1. INTRODUCTION 1-1
2. BACKGROUND INFORMATION 2-1
  2.1 DEFINITIONS 2-1
  2.2 MAJOR SOURCES OF PARTICULATE MATTER 2-2
REFERENCE 2-6
3. PARTICULATE SOURCES 3-1
  3.1 INTERNAL COMBUSTION ENGINES 3-1
    3.1.1 Gasoline Engines 3-1
    3.1.2 Diesel Engines 3-3
  3.2 STATIONARY COMBUSTION SOURCES 3-5
  3.3 INDUSTRIAL PROCESSES 3-9
    3.3.1 Iron and Steel Mills 3-9
      3.3.1.1 Sintering Plants 3-9
      3.3.1.2 Blast Furnaces 3-11
      3.3.1.3 Steelmaking Furnaces 3-12
    3.3.2 Gray Iron Foundries 3-14
    3.3.3 Petroleum Refineries 3-15
    3.3.4 Portland Cement Mines and Factories 3-17
    3.3.5 Kraft Pulp Mills 3-18
    3.3.6 Asphalt Batching Plants 3-19
    3.3.7 Acid Manufacturing Plants 3-20
    3.3.8 Coke Manufacturing Ovens 3-21
    3.3.9 Primary Smelting and Secondary Recovery Facilities for Copper, Lead, Zinc, and Aluminum 3-24
    3.3.10 Soap and Synthetic Plants 3-25
    3.3.11 Glass Furnaces and Glass Fiber Facilities 3-26
    3.3.12 Carbon Black Installations 3-27
    3.3.13 Gypsum Processing Plants 3-27
    3.3.14 Coffee Processing Plants 3-28
    3.3.15 Cotton Ginning Plants 3-29
  3.4 CONSTRUCTION AND DEMOLITION ACTIVITIES 3-29
    3.4.1 Demolition of Masonry 3-30
    3.4.2 Burning of Trash 3-30
    3.4.3 Stirring of Road Dust 3-30
    3.4.4 Grading of Roads 3-31
    3.4.5 Handling of Dusty Materials 3-31
    3.4.6 Sandblasting of Buildings 3-31
  3.5 SOLID WASTE DISPOSAL SITES IN THE UNITED STATES 3-31
    3.5.1 Disposal Without Incineration 3-33
      3.5.1.1 Sanitary Landfill 3-33
      3.5.1.2 Composting 3-34
      3.5.1.3 Shredding 3-35
      3.5.1.4 Compaction 3-36
    3.5.2 Disposal With Incineration 3-36
      3.5.2.1 Open Burning 3-38
      3.5.2.2 Open Top Incinerators 3-38
      3.5.2.3 Conical Metal Burners 3-38
      3.5.2.4 Domestic Incinerators 3-39

TABLE OF CONTENTS (Cont.)

3.5.2.5 Commercial and Industrial Incinerators . . . 3-39
3.5.2.6 Apartment House Incinerators 3-41
3.5.2.7 Municipal Incinerators 3-42
REFERENCES 3-44
4. CONTROL TECHNIQUES 4-1
4.1 SETTLING CHAMBERS 4-9
4.1.1 Description of Equipment 4-9
4.1.2 Operational Factors 4-12
4.1.3 Typical Applications 4-12
4.2 DRY CENTRIFUGAL COLLECTORS 4-12
4.2.1 Description of Equipment 4-13
4.2.2 Operational Factors 4-16
4.2.3 Typical Applications 4-24
4.3 WET COLLECTORS AND MIST ELIMINATORS 4-24
4.3.1 Description of Equipment 4-24
4.3.1.1 Devices Using Energy from Liquid Stream . . 4-24
4.3.1.2 Devices Using Energy from Gaseous Stream . . 4-37
4.3.1.3 Devices That Add Energy Mechanically 4-47
4.3.1.4 Mist Eliminators 4-51
4.3.2 Operational Factors 4-65
4.3.3 Typical Applications 4-69
4.4 HIGH-VOLTAGE ELECTROSTATIC PRECIPITATORS 4-69
4.4.1 Equipment Description 4-71
4.4.2 Operational Factors 4-76
4.4.3 Typical Applications 4-76
4.5 LOW-VOLTAGE ELECTROSTATIC PRECIPITATORS 4-76
4.5.1 Equipment Description 4-76
4.5.2 Operational Factors 4-81
4.5.3 Typical Applications 4-85
4.6 FABRIC FILTERS 4-86
4.6.1 Theoretical Principles 4-86
4.6.1.1 Mechanisms of Filtration 4-86
4.6.1.2 Resistance to Airflow 4-90
4.6.2 Description of Equipment 4-90
4.6.2.1 Bag Shapes 4-97
4.6.2.2 Cloth Types 4-97
4.6.3 Operational Factors 4-104
4.6.3.1 Fabric Filter Cleaning Methods 4-112
4.6.3.2 Dust-Handling and Gas-Cooling Equipment . . 4-118
4.6.4 Typical Applications 4-120
4.6.4.1 Cement Kilns 4-120
4.6.4.2 Foundry Cupolas 4-121
4.6.4.3 Electric Arc Steel Furnaces 4-121
4.6.4.4 Open Hearth Furnaces 4-122
4.6.4.5 Nonferrous Metal Furnaces 4-122
4.6.4.6 Carbon Black Plants 4-123
4.6.4.7 Grain Handling Operations 4-123
4.7 AFTERBURNERS 4-124
REFERENCES 4-129
5. EMISSION FACTORS FOR PARTICULATE SOURCES 5-1
REFERENCE 5-15

SUMMARY

Particulate material found in ambient air originates from both stationary and mobile sources. Of the 23.8 Gkg of particulate pollution produced by industrial, commercial, and domestic sources in 1970, 12.1 Gkg were emitted from industrial sources, including industrial fuel burning; 11.0 Gkg from power generation, incineration, and space heating; and 0.7 Gkg from mobile sources.

PARTICULATE SOURCES

Internal Combustion Engines

For each 4.55 m^3 of fuel consumed, diesel-fueled engines produce about 5.9 kg of particulate matter; gasoline-fueled engines produce about 3.9 kg. Gasoline engine-produced particulate matter emanates from the crankcase and exhaust gases. It consists of carbon, metallic ash, aerosol hydrocarbons, and metallic particles. The particulate matter emitted from a diesel engine consists of carbon and hydrocarbon aerosols.

Stationary Combustion Sources

About 95 percent of the total energy in the United States is supplied by fossil fuels. In 1969, coal supplied about 21 percent of the energy; petroleum, about 40 percent; and natural gas, about 36 percent. Particulate emissions from these sources were about 8.1 Gkg in 1968, but were reduced to about 6.1 Gkg in 1970.

Industrial Sources

Industrial processes, including industrial fuel burning, discharged an estimated 12.1 Gkg of particulate materials in 1970.

Construction and Demolition

The principal demolition, construction, and related operations that generate particulate air pollution are demolition dust, smoke from open burning, road and earth-moving dust, and process particulate matter from paving, sandblasting, and spray painting.

Solid Waste Disposal

In the United States, 2.5 kg/day per person of refuse and garbage is collected. Other solid waste amounts to 2.0 kg/day per person. Very little of this waste is disposed of by nonincineration techniques; open burning is the dominant method of disposition. Particulate emissions from waste disposal were 1.3 Gkg in 1970.

CONTROL METHODS

Techniques for controlling particulate air pollution from stationary combustion sources may be broadly categorized as: source relocation, source shutdown, energy substitution, energy conservation, good practice, and gas cleaning. Of these, gas cleaning is by far the most important.

EMISSION FACTORS

Emission factors may be used to estimate emissions from sources for which accurate stack test results are unavailable. Process emission factors for selected source types are presented in Chapter 5.

1. INTRODUCTION

Particulate matter in the atmosphere is known to have many adverse effects upon health and welfare, and reduction of emissions of this pollutant is of prime importance to any effective air pollution abatement program. This document has been prepared to summarize current information on particulate air pollutants--sources and methods of control.

Particulate pollutants originate from a variety of sources, and the emissions vary widely in physical and chemical characteristics. The many agricultural, commercial, domestic, industrial, and municipal sources of particulate air pollutants are described individually in this document. The nature and quantities of the emissions from the various processes are discussed, and methods of control that have been successfully applied are listed.

The control techniques described herein represent a broad spectrum of information from many engineering and other technical fields. The devices, methods, and principles have been developed and used over many years, and much experience has been gained in their application. They are the techniques generally applicable to the broad range of particulate emission control problems.

A tabulation of emission factors from which overall emissions for the various sources can be estimated is presented. Although the factors are normally for the sources with no control, where applicable, emission factors are given for representative types of control.

Data which apply to the Federal German Republic are referenced as "BRD" (Bundes Republik Deutschland).

2. BACKGROUND INFORMATION

2.1 DEFINITIONS

This section contains general definitions of the terms used throughout this document.

Pollutant or Contaminant--any solid, liquid, or gaseous matter in the outdoor atmosphere which is not normally present in natural air.

Particulate Matter--as related to control technology, any material, except uncombined water, that exists as a solid or liquid in the atmosphere or in a gas stream at standard conditions.

It is important that standard conditions for the measurement of particulate matter be included with its definition. Some compounds are not solids or liquids at stack conditions but condense in the ambient atmosphere. Unless standard conditions for measurement of particulate matter are defined, these materials would not be considered particulate and subject to control.

Aerosol--a dispersion in gaseous media of solid or liquid particles of microscopic size, such as smoke, fog, or mist.

Dust--solid particles predominantly larger than colloidal size and capable of temporary suspension in air and other gases. Derivation from larger masses through the application of physical force is usually implied.

Fly Ash--finely divided particles of ash entrained in flue gases arising from the combustion of fuel. The particles of ash may contain unburned fuel and minerals.

Fog--visible aerosols in which the dispersed phase is liquid. In meteorology, fog is a dispersion of water or ice.

Fume--particles formed by condensation, sublimation, or chemical reaction, of which the predominant part, by weight, consists of particles smaller than 1 micron. Tobacco smoke and condensed metal oxides are examples of fume.

Mist--low-concentration dispersion of relatively small liquid droplets. In meteorology, the term mist applies to a light dispersion of water droplets of sufficient size to fall from the air.

Particle--small, discrete mass of solid or liquid matter.

Smoke--small gasborne particles resulting from incomplete combustion. Such particles consist predominantly of carbon and other combustible material, and are present in sufficient quantity to be observable independently of other solids.

Soot-- an agglomeration of carbon particles impregnated with "tar", formed in the incomplete combustion of carbonaceous material.

Sprays--liquid droplets formed by mechanical action.

2.2 MAJOR SOURCES OF PARTICULATE MATTER

An estimated 23.8 Gkg of particulate matter were emitted from industrial, commercial, and domestic sources in the United States during 1970. Table 2-1

Table 2-1. - PARTICULATE EMISSIONS BY SOURCE CATEGORY, 1970[1]

Source	Quantity (Gkg)	Percent of total
Transportation	0.72	3.0
Fuel combustion (stationary)	6.08	26.0
Industrial processes	12.07	51.0
Refuse disposal	1.27	5.0
Miscellaneous	3.63	15.0
	23.77	100.0

Table 2-2. - INDUSTRIAL PROCESS SUMMARY

Industry or process	Source of emissions	Particulate matter
Iron and steel mills	Blast furnaces, steel making furnaces, sintering machines.	Iron oxide, dust, smoke.
Gray iron foundries	Cupolas, shake out systems, core making.	Iron oxide, dust, smoke, oil, grease, metal fumes.
Metallurgical (non-ferrous)	Smelters and furnaces.	Smoke, metal fumes, oil, grease.
Petroleum refineries	Catalyst regenerators, sludge incinerators.	Catalyst dust, ash from sludge.
Portland cement	Kilns, dryers, material handling systems.	Alkali and process dusts.
Kraft paper mills	Chemical recovery furnaces, smelt tanks, lime kilns.	Chemical dusts.
Acid manufacture-phosphoric, sulfuric	Thermal processes, phosphate rock acidulating, grinding, and handling systems.	Acid mist, dust.
Coke manufacturing	Charging and discharging oven cells, quenching, materials handling.	Coal and coke dusts, coal tars.
Glass and glass fiber	Raw materials handling, glass furnaces, fiberglass forming and curing.	Sulfuric acid mist, raw materials dusts, alkaline oxides, resin aerosols.
Coffee processing	Roasters, spray dryers, waste heat boilers,coolers, conveying equipment.	Chaff, oil aerosols, ash from chaff burning, dehydrated coffee dusts.

Table 2-3. - ADVANTAGES AND DISADVANTAGES OF COLLECTION DEVICES

Collector	Advantages	Disadvantages
Gravitational	Low pressure loss; simplicity of design and maintainance.	Much space required; low collection efficiency.
Cyclone	Low to moderate pressure loss; simplicity of design and maintainance; little floor space required; dry continuous disposal of collected dusts; handles large particles and high dust loadings; temperature independent.	Much headroom required; low collection efficiency of small particles; sensitive to variable dust loadings and flow rates.
Wet collectors	Simultaneous gas absorption and particle removal; colls and cleans high-temperature, moisture-laden gases; corrosive gases and mists can be recovered and neutralized; reduced dust explosion risk; efficiency can be varied.	Corrosion, erosion problems; added cost of wastewater treatment and reclamation; low efficiency on submicron particles; contamination of effluent stream of liquid entrainment; freezing problems in cold weather; reduced buoyancy and plume rise; water vapor adds to visible plume in some atmospheric conditions.
Electrostatic precipitator	99+ percent efficiency obtainable; very small particles can be collected wet or or dry; small pressure drop and power requirement compared to other high-efficiency collectors; nominal maintenance unless corrosive or adhesive materials are handled; few moving parts; can be operated at 560 to 730 K.	Relatively high initial cost; sensitive to variable dust loadings or flow rates; resistivity causes some material to be economically uncollectable; precautions required to safeguard personnel from high voltage; collection efficiency can deteriorate gradually and imperceptibly.
Fabric filtration	Dry collection possible; decrease in performance noticeable; collection of small particles possible, high efficiencies possible.	Sensitive to filtering velocity; high-temperature gases must be cooled to 370 to 560 K; affected by relative humidity (condensation); fabric susceptible to chemical attack.

Table 2-3. (cont.)

Collector	Advantages	Disadvantages
Afterburner, direct flame	High removal efficiency of submicron odor-causing particulates; simultaneous disposal of combustible gases and particulates; direct disposal of nontoxic gases and gases and wastes to atmosphere after combustion; possible heat recovery; relatively small space requirement; simple construction; low maintenance.	High operational cost; fire hazard; removes only combustibles.
Afterburner, catalytic	Same as direct flame afterburner. Reduced fuel requirements and reduced temperature.	High initial cost; catalyst subject to poisoning; catalyst requires reactivation; insulation requirements; fire hazard.

shows the contribution to this total from each source category. Stationary fuel combustion and industrial processes are the largest individual emitters of particulate pollution. Table 2-2 presents a summary of important industries, their pollutant sources, and types of particulate pollutants. Table 2-3 lists the methods of gas cleaning, their advantages and disadvantages.

REFERENCE

1. CAP Data File of Nationwide Emission, 1970. National Air Data Center, Applied Technology Division, July 1972.

3. PARTICULATE SOURCES

3.1 INTERNAL COMBUSTION ENGINES

Gasoline engines produce particulates at about 1.0 kg/m^3 of liquid fuel consumed; diesels produce about 1.54 kg/m^3.[1] Of the total annual particulate emissions in the United States, motor vehicles contribute approximately 4 percent. Table 3-1 compares contributions by motor vehicles to total particulate emissions in different U.S. communities.

3.1.1 Gasoline Engines

Gasoline engines generate particulates from two sources, the engine exhaust and the crankcase blowby. As a rough approximation, the amount of particulate matter emitted in blowby gases is one-third to one-half the amount emitted in the exhaust.[1]

In automobile exhaust, the weight of particulates is approximately 5 percent of the weight of gaseous hydrocarbons. Lead compounds, carbon particles, and nonvolatile substances from motor oil are emitted and may react to form high-molecular-weight olefins and carbonyl compounds. Metal-based particles result primarily from lead antiknock compounds in the fuel and also from metallic lubricating oil additives and from engine wear; carbon and some of the hydrocarbon aerosols result from incomplete fuel combustion.

In blowby gases, particles are almost entirely unchanged lubricating oil. Blowby emissions are influenced to a greater extent than exhaust emissions by mechanical condition of the engine.[8]

Partial control of vehicle particulate emissions has been in effect in the United States since 1963. Beginning with the 1968 automobile models,

Table 3-1. - COMPARISON OF MOTOR VEHICLE PARTICULATE EMISSIONS WITH TOTAL PARTICULATE EMISSIONS FOR SELECTED AREAS IN THE UNITED STATES[2-7]

Metropolitan area	Particulate matter, Mkg/yr		
	Total	Motor vehicles	Percent of total from motor vehicles
Washington, D.C.	31.8	5.17	16
New York--Northern New Jersey	211.0	30.7	15
Kansas City	54.3	4.5	8
Jacksonville, Florida	12.8	0.55	4
St. Louis, Missouri	133.0	4.25	3
Los Angeles County, California	39.0	14.9	38

particulate emissions from crankcases were completely controlled (Fig. 3-1), and it is possible the exhaust control measures used in these models reduce the exhaust emissions of particulates.

Lead emissions can be controlled by restricting the concentration of antiknock compounds in the fuel. Petroleum processing equipment is now producing unleaded gasoline; its availability is becoming widespread.

3.1.2 Diesel Engines

Particulates emitted by diesel engines are primarily carbon and hydrocarbon aerosols resulting from incomplete combustion of the fuel. Aerosols in the vent gases add a small amount.

Federal regulations implemented in the United States in 1971[9] to limit smoke from new diesel engines establish a maximum intensity of smoke emission under conditions of (1) full-throttle acceleration from a prolonged idle and (2) "lugdown" from maximum governed speed, also at full throttle. No new information or control devices are believed to be needed to reduce the smoke emissions from diesel engines to meet the established standards.

New engines, which will comply with the 1971 smoke standards, will be adjusted by the manufacturers to a conservative fuel rate and power output. Increases in fuel rate above the manufacturer's setting will increase engine power but will also raise the level of black smoke. Even in a properly adjusted engine, injector deterioration (such as nozzle erosion) can effect a substantial increase in the emission of black smoke. As vehicles age and mileage increases, proper adjustment of the fuel system, maintenance at appropriate intervals, use of the specified type of fuel, and application of good operating techniques can maintain low levels of visible emissions, particularly carbon particles.

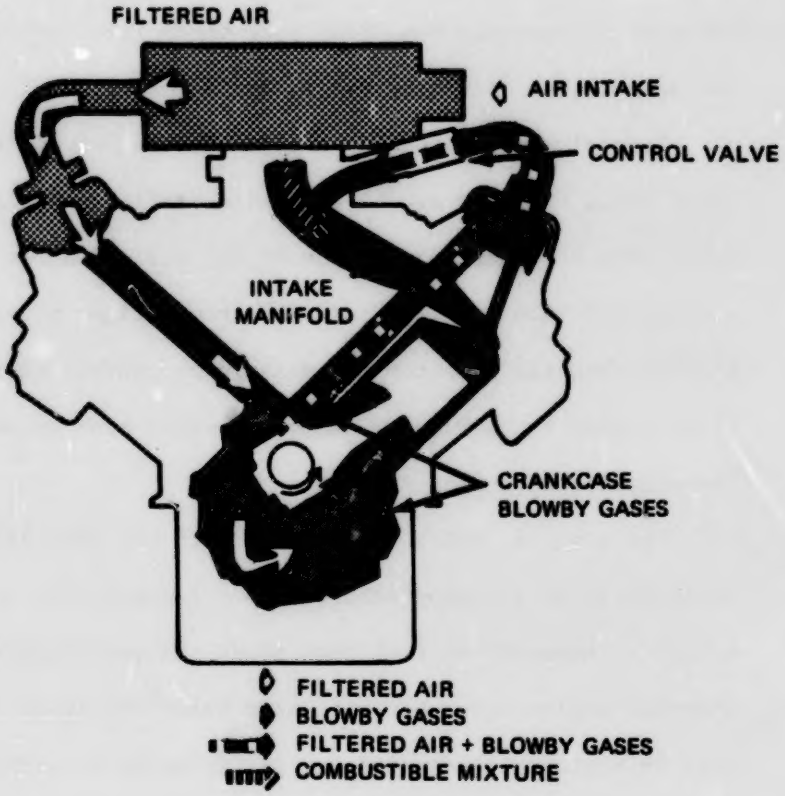
FILTERED AIR
AIR INTAKE
CONTROL VALVE
INTAKE MANIFOLD
CRANKCASE BLOWBY GASES
FILTERED AIR
BLOWBY GASES
FILTERED AIR + BLOWBY GASES
COMBUSTIBLE MIXTURE

Fig. 3-1. Motor vehicle emission control system.

Fortunately, particulate pollution from diesels can be reduced to a satisfactory level with engine tuning, since other methods of pollution control--primarily exhaust gas dilution and the use of smoke-suppressing fuel additives--are less effective and cannot be recommended for general application. Dilution merely reduces the opacity of the smoke plume without reducing the quantity of particles emitted. Smoke suppressants are effective in overfueled engines in good mechanical condition. However, one promising suppressant contains a barium additive,[10] which could lead to emissions of toxic, water soluble barium compounds; thus further study is needed before this technology is broadly adopted.

3.2 STATIONARY COMBUSTION SOURCES

Although some miscellaneous fuels (liquified petroleum gas, wood, lignite, coke, refinery gas, blast furnace gas, etc.) are utilized, about 95 percent of the total energy in the United States is supplied by coal, oil, and natural gas. Recent trends in the utilization of these resources are given in Tables 3-2 and 3-3.* Tables 3-4 and 3-5 show the fuel consumption by type of consumer. Table 3-6 shows the wide variety of equipment available for combustion processes. Particulate emissions from stationary combustion sources for 1968 were estimated at 8 Gkg.[11]

Because the rate of emission varies widely from unit to unit, the amount of particulates expected from each source has not been established with accuracy. Data for estimating emissions from groups of units are reported as emission factors in Section 5.

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*Data from the Federal German Republic will be referenced as "BRD" (Bundes Republik Deutchland).

Table 3-2. - U.S. MINERAL ENERGY RESOURCES AND ELECTRICITY--PRODUCTION AND CONSUMPTION: 1965 TO 1969[11]

[In 10^{15} Joules]

Year	Total	Coal		Crude petroleum[a]	Natural gas[b]	Electricity
		Anthracite	Bituminous and lignite			
1965	57 000	346	12 700	22 800	21 200	2 220
1966	60 500	306	13 500	24 000	20 500	2 230
1967	62 500	290	13 300	24 800	21 600	2 530
1968	66 000	273	13 800	26 200	23 100	2 590
1969 (prel.)	69 300	257	14 000	27 400	24 800	2 970

[a] Includes commingled condensate. Beginning 1950, consumption includes petroleum products (net imports).

[b] Marketed production. Includes amount stored and lost in transmission. Consumption includes dry and liquid. Beginning 1965, on pressure base of 101.54 kN/m^2 absolute; formerly, on base of 96.86 kN/m^2.

Table 3-3. - BRD MINERAL ENERGY RESOURCES AND ELECTRICITY--PRODUCTION AND CONSUMPTION: 1966 TO 1969[12]

[In 10^{15} Joules]

Year	Total	Coal	Petroleum products	Miscellaneous	Gas	Electricity
1966	5 806	1 760	2 850	124	512	560
1968	6 244	1 595	3 230	143	636	640
1969	6 853	1 600	3 670	163	713	707

Table 3-4. - U.S. CONSUMPTION OF ENERGY RESOURCES BY MAJOR CONSUMER GROUP: 1963 TO 1968[11]

[In 10^{15} Joules]

Consumer group	Energy inputs			
	1963	1965	1967	1968 (prel.)
Household and commercial	11 700	12 500	13 800	14 400
Industrial	17 200	18 700	19 600	20 400
Transportation[a]	12 630	13 400	14 900	16 000
Electrical generation, utilities[b]	10 200	11 700	13 800	14 800
Miscellaneous	780	579	293	356
Total	52 510	56 879	62 393	65 956

[a] Includes bunkers and military transportation.

[b] Represents outputs of hydropower and nuclear power converted to theoretical energy inputs at prevailing rate of kg of coal per kilowatt-hour at central electric stations using 27.8 MJ/kg coal. Excludes inputs for power generated by nonutility plants which are included within the other consuming sectors.

Table 3-5. - BRD CONSUMPTION OF ENERGY RESOURCES BY MAJOR CONSUMER GROUP: 1960 TO 1969[12]

[In 10^{15} Joules]

Consumer group	Energy inputs				
	1960	1964	1967	1968	1969
Household and commercial	1 650	2 310	2 440	2 625	2 970
Industrial	2 220	2 440	2 380	2 560	2 740
Transportation	710	922	1 006	1 060	1 135
Electrical generation	1 330	1 730	1 820	1 990	2 260
Miscellaneous	726	676	736	835	806
Total	6 636	8 078	8 382	9 070	9 911

Table 3-6. - COMMON USES OF VARIOUS
FUEL-BURNING EQUIPMENT

Equipment	Common use
Coal-fired:	
Hand-stoked equipment	Residential, institutional, and commercial warm-air and boiler applications at capacities up to 5.3 GJ/hr. (Used primarily in coal-producing areas.)
Single-retort underfeed stokers	Residential, institutional, and commercial warm-air and boiler applications at capacities up to 42.2 GJ/hr input.
Multiple-retort underfeed stokers Spreader stokers Traveling grate stokers Chain grate stokers Vibrating grate stokers	Water tube and fire tube boiler applications for institutional, commercial, and industrial heating at capacities in range of 5.3 to 212 GJ/hr input.
Pulverized-fuel-fired equipment (dry bottom or wet bottom)	Water tube boiler applications for power generation at capacities greater than 106 GJ/hr input.
Oil-fired:	
High-pressure gun-type burners	Residential warm air furnace or boiler applications at capacities up to 11.4 dm^3/hr distillate oil.
Low-pressure air-atomizing burners	Water tube and fire tube boiler applications for institutional, commercial, and industrial process heating with distillate or residual oil.
Rotary cup burners Steam atomizing burners High-pressure air-atomizing burners	Water tube and fire tube boiler applications for institutional, commercial, and industrial heating and power generation with residual oil.
Gas-fired:	
Premixing burners	Residential warm-air furnace or boiler applications and low-temperature industrial applications.
Nozzle mixing burners	Water tube and fire tube boiler applications for institutional, commercial, industrial, and power-generation applications. (May be combination type to permit fuel oil firing when gas supply is interrupted.)

3.3 INDUSTRIAL PROCESSES

Approximately 7.3 Gkg of dust, fume, and mist were discharged in the United States from industrial processes and industrial fuels fired in 1968.[11]

Some industries create more particulate emissions than other, and within those industries one or two specific processes dominate the emission picture. Often these emissions can be reduced dramatically through modifications to those specific processes.

Table 3-7 lists many of the industries that release large quantities of dry dusts, combustible oil and tar mists, inorganic acid mists, and combinations of these and other pollutants. The same industries frequently release gaseous pollutants which are more objectionalbe than the particulates. Although this discussion is limited to particulates, some remedial measures also affect sulfur oxides (SO_2), odors, or other gaseous contaminants.

The 15 industrial sources cited in the following pages commonly use several types of fired heaters and boilers. Particulate emissions associated with this equipment depend on the fuel burned. Combustion processes, discussed in another section, are cited here if specific problems are associated with them.

3.3.1 Iron and Steel Mills

The major sources of particulates in iron and steel mills are sintering plants, blast furnaces, and steelmaking furnaces.

3.3.1.1 Sintering Plants--Major sources of dust in sintering plants are the combustion gases drawn through the bed and the exhaust gases from sinter grinding, screening, and cooling.[24] In combustion gases, exhaust temperatures range from 340 to 475 K, and 50 percent (by weight) of the particles are larger than 100 μm.[14]

Table 3-7. - INDUSTRIAL PROCESS SUMMARY

Industry or process	Particulate emissions		Other emissions	Reference
	Nature	Principal sources		
1. Iron and steel mills	Iron oxide dust, smoke.	Blast furnaces, steelmaking furnaces, sintering machines.	CO, combustion products.	13,14
2. Gray iron foundries	Iron oxide dust, smoke, oil and grease, metal fumes.	Cupolas, shakeout systems, core making.	Odors, combustion products, hydrocarbons from contaminated scrap.	15,16,17
3. Petroleum refineries and asphalt blowing	Catalyst dust, ash, sulfuric acid mist, liquid aerosols.	Catalyst regenerator, sludge incineration, air blowing of asphalt.	Hydrocarbons, SO_x, H_2S, odors.	15,18
4. Portland cement	Alkali and product dusts.	Kilns, coolers, dryers, material handling systems.	Combustion products.	15,19
5. Kraft pulp mills	Chemical dusts, mists.	Chemical reclaiming furnaces, smelt tanks, lime kilns.	Odors, SO_x.	20
6. Asphalt batch plants	Aggregate dusts.	Dryers, material handling systems.	Odors, combustion products.	
7. Acid manufacture: Phosphoric Sulfuric	Acid mist, dust. Acid mist.	Thermal processes--phosphate rock acidulating, grinding and handling systems.	HF, SO_x, odors.	21
8. Coke manufacturing	Coal and coke dusts, coal tars.	Charging and discharging oven cells, quenching, material handling.	Phenols, H_2S.	13
9. Primary and secondary facilities for copper, lead, zinc, and aluminum	Smoke, metal fumes, oil and grease.	Smelting and melting furnaces.	SO_x, combustion products.	11,15
10. Soap and detergent manufacturing	Detergent dusts.	Spray dryers, product and raw material handling systems.	Combustion products, odors.	
11. Glass furnaces and glass fiber manufacture	Sulfuric acid mist, raw material dusts, alkaline oxides, resin aerosols.	Raw material handling, glass furnaces, glass fiber forming and curing.	Combustion products.	
12. Carbon black	Carbon black.	Carbon black generators.		
13. Gypsum processing	Product dusts.	Calciners, dryers, grinding and material handling systems.	Combustion products.	22
14. Coffee processing	Chaff, oil aerosols, ash dehydrated coffee dusts.	Roasters, spray dryers, waste heat boilers, coolers, stoners, conveying equipment, chaff burning.		
15. Cotton ginning	Cotton fiber, dust, and smoke.	Gins, trash incineration.	Defoliants and insecticides.	23

In the BRD, exhaust temperatures range from 375 to 675 K. Particle loading before control equipment is up to 20 g/Nm^3. Specific offgas is 1 to 4 Nm^3/kg of sinter.[28] Iron compounds account for up to 50 percent of the dust; SiO_2 and CaO, 15 to 20 percent. The rest consists of MgO, Al_2O_3, C, S, and alkalies.

Because dust generated in sintering can be returned to the process, most plants are equipped with cyclones, which usually operate at over 90-percent efficiency; still, cyclone exit loadings range from 0.45 to 1.4 g/m^3. High-efficiency baghouses offer promise of much better collection, but few have been applied to sintering machines.[25] Electrostatic precipitators are becoming more popular for controlling sintering plant emissions, with 29 precipitators existing in 19 installations in the United States in 1968.[26]

BRD practice shows cyclone efficiencies between 75 and 95 percent maximum, with exist loading of 0.3 g/Nm^3 (guaranty during continuous load).[27] Electrostatic precipitators have an exit loading up to 0.150 g/Nm^3 during continuous load.[28]

3.3.1.2 Blast Furnaces--Iron ore, coke, and limestone are charged into a blast furnace to make iron. Under normal conditions, the untreated gases from the furnace contain from 18 to 70 g/Nm^3 of dust,[29] and most of the particles are larger than 50μm. The dust contains about 30 percent iron, 15 percent carbon, 10 percent silicon dioxide, and small amounts of aluminum oxide, manganese oxide, calcium oxide, and other materials. Blast furnace gas-cleaning systems normally reduce particulate loading to less than 23 mg/Nm^3 to prevent fouling of the stoves where the gas is burned. These systems are usually composed of settling chambers and low-efficiency wet scrubbers followed by high-efficiency wet scrubbers or electrostatic precipitators.[30]

BRD reports lower loading of untreated blast furnace gases (10 to 50 g/Nm^3) with water content of 50 to 60 g/Nm^3.[27] Cleaning systems reduce particulates to 5 to 15 mg/Nm^3.[27] Since high scrap feed is used, emissions are 6 to 15 percent Fe_2O_3, 20 to 50 percent ZnO, 5 percent PbO, 10 to 15 percent alkali oxides, and 20 percent sulfur as SO_3.

3.3.1.3 Steelmaking Furnaces--The three most important types of steelmaking furnaces are open hearth furnaces, basic oxygen furnaces, and electric furnaces. Relative usage as percentage of total production of each furnace type from 1965 through 1969 is shown in Table 3-8 and 3-9.

Average emission rate from a hot metal open hearth furnace is about 0.9 g/Nm^3 for a conventional furnace and 2.3 g/Nm^3 for an oxygen-lanced furnace.[32,33] Up to 90 percent of the particles are iron oxide, predominantly Fe_2O_3. About 50 percent of the particles emitted throughout a heat are less than 5 μm. Control of iron oxide requires high-efficiency collection equipment such as venturi scrubbers and electrostatic precipitators. Because of the cost and the growing obsolescence of open hearth furnaces, industry has been reluctant to invest in the required control equipment.[33] Often these furnaces have been replaced by controlled basic osygen furnaces and electric furnaces.

More emissions are created by the basic oxygen furnace than by the open hearth furnace. Higher emissions are caused by oxygen blowing, with emissions of about 11g/Nm^3 being typical.[34] Particles are small--85 percent are less than 1 μm.[35] One reference reports this size distribution to be between 30 and 200 μm.[36] All basic oxygen furnaces in the United

Table 3-8. - U.S. RAW STEEL PRODUCTION: 1965 TO 1969[11]

Year	Total Mkg	Percent of total		
		Open hearth[a]	Electric	Basic oxygen process
1965	121 000	72	11	17
1966	121 500	64	11	25
1967	115 000	56	12	33
1968	121 000	50	13	37
1969	128 000	43	14	43

[a] Includes bessemer.

Table 3-9. - BRD RAW STEEL PRODUCTION: 1965 TO 1970[31]

Year	Total Mkg	Percent of total		
		Open hearth[a]	Electric	Basic oxygen process
1965	36 821	72	9	19
1967	36 744	60	9	31
1969	45 316	45	9	46
1970	45 041	34	10	56
1971	40 313	28	10	62

[a] Includes bessemer.

States are equipped with high-efficiency electrostatic precipitators or venturi scrubbers.

In the BRD, of the seven bottom blowing steelmaking furnaces (145 000 kg capacity each), two are fully controlled and two more are to be controlled by 1973. Baghouses with fabric filters (polyester) are also used for control in the BRD.

Electric furnaces are usually used for alloy production, and because of their flexibility, are becoming popular for most metal-melting operations. Emissions from electric furnaces often reach 7 g/Nm^3; only 40 to 50 percent of the dust is iron oxide, an amount considerably less than that emitted by other furnaces. The particles are difficult to collect because they have a strong tendency to adhere to fabric surfaces, a high angle of repose, a high electrical resisitivity, and a strong hydrophobicity. Approximately 70 percent by weight of the particles are smaller than 5 μm, and 95 percent by number are smaller than 0.5 μm.[37] Nevertheless, over 95-percent effective collection can be achieved with appropriate hooding and high-efficiency collection equipment. Baghouses are especially suited for such collection.

3.3.2 Gray Iron Foundries

Melting cupolas are the principal sources of particulates at iron foundries. Casting shakeout systems, sand-handling systems, grinding and deburring operations, and coke-baking ovens are other sources.

Of the total air-polluting particulates emitted by raw steel producers in the BRD (72 Mkg/yr), it is estimated that 28 percent of this comes from gray iron foundries.

For a cupola, the most effective control system incorporates an afterburner to eliminate combustibles and a fabric filter to collect the inorganic dust and fume. Coolers are used ahead of the baghouse to protect fabric filters from the heat of the voluminous exhaust gases. Most use glass fabrics; some use synthetic cloths.

In the BRD it is porposed to enclose the complete dusty operation, starting with the cupolas. All ambient dusts will be passed through air coolers and baghouses.

Even though baghouse control systems provide excellent particle collection, they are not widely accepted, mainly because of cost.[38] Dry centrifugal collectors and scrubbers with various efficiencies are used by many. High-efficiency scrubbers are reported to provide about the same performance as fabric filters, but visible emissions are more pronounced.

Casting shakeout and sand handling are dusty operations that are normally well controlled. Baghouses are commonly used; medium-efficiency scrubbers and dry centrifugal collectors are also used.

Core ovens create relatively small quantities of particulates, much of which is finely divided liquid aerosols. Emissions from core ovens are similar to those discharged from paint-baking and resin-curing operations, but odors are more objectionable. A properly designed afterburner will eliminate most of the particulates and odors.

3.3.3 Petroleum Refineries

Major sources of particulates at petroleum refineries are catalyst regenerators, airblown asphalt stills, and sludge burners. Lesser sources include fired heaters, boilers, and emergency flares.

In modern fluidized catalytic crackers, fine catalysts are circulated through the reactor and the regenerator vessels. A typical large regenerator will vent from 50 to 70 m^3/s of hot, dusty gases. Dust collectors, as well as carbon monoxide waste heat boilers, are often used to control emissions; a carbon monoxide boiler can use the fuel value of the clean gas exiting from the dust collector. Typically, two- or three-stage cyclones are installed in the regenerator vessels of fluidized catalytic cracking (FCC) units to recover the catalyst; in some cases, external cyclones are installed to reduce the particulate content of the exiting flue gases. Catalyst dust losses from the regenerator equipped with internal cyclones, and in some cases supplemented by external cyclones, range from 13 to 45 g/s depending on the size, age, and design of the unit. Refiners who use electrostatic precipitators to collect the fine particles from the regenerator exit gases have reported catalyst dust losses as low as 5 to 8 g/s; the efficiency depends on the inlet dust-loading from the regenerator and the desired emission rate to the atmosphere.

Airblowing of asphalts generates oil and tar mists and odorous gases. It is common practice to scrub the oils and tars from the hot (420 to 480 K) gas stream. Sea water is sometimes used for this purpose. In any case, separators are used to reclaim the oil and prevent contamination of effluent water, and afterburners are used to incinerate the uncondensed gases and vapors. Packed fiber beds are also used to eliminate oil and tar mists as well as odorous gases.

At petroleum refineries, the open burning of sludges can be a major source of particulate and sulfur dioxide emissions. Sludges are mixtures of heavy petroleum residues and inorganic materials (e.g., clay, sand,

and acids). For incineration, sludge is usually atomized in much the same way as heavy fuel oil. The organic fraction can be effectively incinerated, but the inorganic is entrained in exhaust gases from which it must be collected by either high-efficiency precipitators, baghouses, or high-energy scrubbers. Solvent extraction is another method for recovering the organic fraction; the separated "clean" solids can be disposed of in landfills. To collect the sulfur dioxide, not affected by these methods, the sludge can be conditioned and used in the feed to a sulfuric acid plant. Very low grade sludges may be dumped at sea.

3.3.4 Portland Cement Mines and Factories

Both mining of raw materials and manufacture of cement create dust. Dust is generated during blasthole drilling at the quarry, during blasting at the rock face, and during loading of trucks. At primary and secondary crushing plants, in grinding mills, at blending and transfer points, and in final bagfilling and bulk (truck or railroad car) loading operations where the particulate-laden air is at ambient temperatures, bag filters are usually the best means of control.[39]

Rotary dryers used in dry process cement plants can be major sources of dust--concentrations of 12 to 23 g/Nm^3. Baghouses or combinations of multiple cyclones and baghouses are frequently used. Newer dry process cement plants incorporate the drying operation into the raw grinding circuit; in such a "dry-in-the-mill" combination, drying and grinding dusts are normally vented to a baghouse.

The major sources of emissions at cement plants are direct-fired kilns for burning portland cement clinker. Exit gas particulate loadings are usually 12 to 23 g/Nm^3 for wet kilns and 25 to 45 g/Nm^3 for dry process kilns. The volume of the hot 530 to 590 K kiln gases may exceed 120 m^3/s. Over 85 percent by weight of gasborne particles are smaller than 20 μm. The chemical constituents are calcium oxide (CaO), about 41 percent; silicon dioxide (SiO_2), 19 percent; aluminum and iron oxides ($Al_2O_3 + Fe_2O_3$), 9 percent; and carbon dioxide (CO_2), about 31 percent.[40] Electrostatic precipitators and fabric filters are widely used to control particulate emissions from both wet and dry process kilns, but precipitators sometimes fail to give adequate control.[41] In the BRD electric precipitators with efficiencies of 98 to 99.9 percent are used with dust concentrations of 80 to 620 mg/Nm^3 in the exit gases.[42]

3.3.5 Kraft Pulp Mills

The major source of particulates in kraft pulping is the recovery furnace where spent cooking liquors are burned to remove the organic materials dissolved from the wood and to recover the inorganic cooking chemicals. Sodium sulfate is the major particulate emission. Small amounts of sodium carbonate, salt, and silica, and traces of lime, iron oxide, alumina, and potash also are emitted. Because 95 to 98 percent of the total alkali charged to the digester finds its way to the spent liquor, it is economically imperative that it be recovered. Electrostatic precipitators of about 90-percent efficiency are used for recovery furnaces,[1] but specifications for the 1970's often call for design efficiencies of about 99 percent.[26] Newer experiments with packed fiber beds seem to meet these 1970 specifications.[43]

Other sources of particulates are smelt tanks and lime kilns. Stack dust from lime kilns can be collected in 85 to 90 percent efficient venturi scrubbers. Water sprays of 20 to 30 percent efficiency and mesh demisters of 80 to 90 percent efficiency are usually used on smelt tanks.

3.3.6 Asphalt Batching Plants

Asphalt batching plants are potential sources of heavy dust emissions. Asphalt batching involves the mixing of hot, dry sand, aggregate, and mineral dust with hot asphalt.

Although conveyors and elevators generate some dust, the major source is the direct-fired dryer used to dry and heat aggregates. Exit gases range from 400 to 530 K at volume rates of 6 to 25 Nm^3/s. Most dryers have simple cyclone separators which collect 70 to 90 percent of the dust entrained in the exit gases. Nevertheless, the remaining dust in the gas stream usually totals more than 126 g/s, so additional dust controls are frequently needed. In many areas, centrifugal and baffled scrubbers control the fine dust which escapes the primary cyclone; some exceed 99.0 percent efficiency--with losses ranging from 2.5 to 5 g/s. It is common to vent elevators and major conveyor transfer points to the scrubber.[44]

In the BRD the dust content of the controlled gas varies between 10 and 150 g/Nm^3. Exit concentrations in excess of 100 g/Nm^3 are not permitted. Baghouses and wet scrubbers are used for control.[45]

High-temperature fabric filters have been used successfully at asphalt batching plants since 1950. Several installed in Chicago, Illinois, provide excellent collection of fine particles with little or no visible emissions from the baghouse. Although fabric filters frequently are mosre expensive than scrubbers, they collect dry fines which can be usable in high-grade asphalt concrete mixes, they obviate the need for holding ponds and they preclude water problems.

3.3.7 Acid Manufacturing Plants

Most of the particulates attributed to acid manufacture are created in the production of sulfuric and phosphoric acids. Manufacture of the other two major industrial acids--nitric and hydrochloric--does not generate large amounts of acid mist.

Over 90 percent of the sulfuric acid is manufactured by the contact process.[21] In the process, sulfur or sulfur-bearing materials are burned to sulfur dioxide (SO_2) and catalytically converted to sulfur trioxide (SO_3). Uncontrolled emissions range from 0.114 to 0.525 g/Nm^3, depending largely on plant design and on proper operation of the acid absorber. Most modern plants are equipped with high-efficiency electrostatic precipitators or mesh eliminators with 99-percent recovery. Acid mists are usually controlled to a far greater extent than gaseous sulfur dioxide releases.

In the BRD most of the sulfuric acid is produced by the double contact process which is described in Reference 46. Modern plants are equipped with high-efficiency electrostatic precipitators, mesh eliminators, or packed fiber beds with efficiencies of 100 percent for droplets larger than 3 μm and up to 99.9 percent for droplets smaller than 3 μm.[47,48]

Sulfuric acid is also manufactured by the chamber process. The primary source of emissions in this process is the final Gay Lussac tower. Combined acid mist and spray in the exit gas ranges from 0.18 to 1.0 g/Nm^3.

To manufacture phosphoric acid, two processes are used. The one for producing acid for the food and detergent industries is similar to the contact sulfuric acid process. High-purity acid is produced by burning elemental phosphorous to the pentoxide (P_2O_5), which is hydrated and agsorbed in phosphoric acid. High-purity phosphorous is manufactured in electric furnaces, which create gaseous fluorine compounds and solid particulates. Mists are collected from exhaust gases with electrostatic precipitators or high pressure drop, mesh entrainment separators. Mists escaping collection are extremely hygroscopic, so visible emissions are pronounced unless high collection efficiencies are achieved. To reduce visible emission, packed fiber beds with efficiencies up to 99.9 percent are operated.[49]

The wet process produces phosphoric acid for the fertilizer industry by reacting sulfuric acid with phosphate rock. Particulates are generated primarily with material handling and grinding operations. However, the acidulation liberates large quantities of gaseous silicon tetrafluoride (SiF_4), which must be removed with scrubbers.

3.3.8 Coke Manufacturing Ovens

Metallurgical coke is the solid material remaining after distillation of certain coals. About 90 percent of the U.S. coke output is used for production of blast furnace iron.

Conventional coking is done by charging coal through holes in the top of slot type coke ovens. Coke oven gas or other suitable fuel is burned in the flues surrounding the ovens to furnish heat. With a flue temperature of about 1 700 K, the coking period averages 17 to 18 hours. At the end of this period, incandescent coke is pushed out of the furnace into cars and carried to a quenching station, where it is cooled with water sprays.

Coal and coke dust emissions result from coal-car unloading, coal storage, crushing and screening, the coking process (where the largest releases of dust occur during charging of the byproduct oven and pushing of the product coke to quench cars), quenching, and final dumping from the quench car.

Slot type coke ovens include the following features that speed operations and minimize leaks:

1. Better designed, thinner walled heating flues to improve heat transfer and minimize cool spots and undercoking and to give cleaner pushing operation.
2. Improved refractories, with less spalling and cracking, to minimize warping of metal furnace parts, gas leaks into flue systems and chimneys, and voids which fill with undercoked coal and cause smoke during pushing.
3. Gas-tight, self-sealing oven doors to minimize manual sealing with clay.
4. Mechanical cleaners or self-sealers for doors and for top-charging hole covers to minimize leakage of hot gases.
5. Sealing sleeves for leveling bars to smooth the oven charge and allow free passage of gas over the charge into the collector main.
6. Mechanical removal of top coal-charging lids and means to charge all three holes of an oven rapidly and simultaneously, with gas recovery mains in operation.
7. Steam jet aspirators in byproduct header ducts to assist in byproduct collection.
8. An intercell header to normalize the cell pressure throughout the battery.
9. Charging car volumetric sleeves and dust entrainment chutes to minimize particulate losses.
10. Wooden baffling to separate particulates from quench tower effluent gases.

In the BRD it is reported that complete control of coking dusts has been achieved at Essen by covering dust sources with closed systems, using steam jet evacuators, and electrostatic precipitators.

The beehive oven is a simpler type of coking oven from which distillation products are not recovered. Its use has diminished with the development of the slot type, or byproduct, oven; but it has an economic advantage during peak production periods: Capital investment is lower, and inoperative periods can be tolerated. About 1.5 percent of the total coal coked in the United States in 1967 was produced in beehive ovens. About 25 to 30 percent of the coal charged to these ovens is emitted as gases and particulates. Ducting these emissions to an afterburner appears to be a feasible method of control.

Another form of coke, used in blast furnace refractories and in the manufacturing of electrodes for large steel and aluminum reduction furnaces, is calcined petroleum coke. Calcining in a rotary kiln at 1 200 K removes absorbed water and heavy oil and forms a marble-sized product. Volatilized hydrocarbons are usually passed to a combustion chamber of 1 500 K before being released to the atmosphere. Subsequent conveyance of the dusty product to storage requires hooding, enclosed ducting, and special attention to the abrasiveness of the dust. Control of particulates during loading of the coke is accomplished with concentric tubing; the inner filling tube carries the coke, and the outer tube exhausts entrained dust from the enclosed railroad car, truck, or ship hold. Baghouses capture dust from loading as well as dust generated at other handling and transfer points.

For description of BRD technology in the above area, see references 50, 51, and 52.

3.3.9 Primary Smelting and Secondary Recovery Facilities for Copper, Lead, Zinc, and Aluminum

During the primary smelting of lead and zinc, the sulfide of the ore is first converted to an oxide by roasting, and then the oxide is reduced to the metal in a separate vessel. Copper, however, requires a preliminary smelting step--mixing the charge with limestone--to reduce naturally occurring complex sulfide to the cuprous sulfide (CuS_2) so that the sulfide can be converted to blister copper in a converter and sulfur can be removed by oxidation. Sulfur dioxide gas is released along with particulates--mostly sublimed oxides, dust, and acid mists. When sulfur dioxide emissions exceed 3 percent of furnace exhaust volumes, recovery by a sulfuric acid manufacturing plant is feasible and the smelter gases going to the acid plant should be pretreated to remove particulates. Control by sulfuric acid plant is the general route followed in the BRD. Purification equipment consists of cyclones, electrostatic dust and mist precipitators together with scrubbers and gas-cooling towers in various combinations. If sulfur dioxide recovery is not practiced, fiberglass demisters or precipitators are normally used to remove particulates.

Most materials fed to secondary recovery furnaces are alloys of copper, zinc, tin, or lead in the form of solid scrap and drosses. Gases from furnaces may contain oxide fumes of the low-boiling metals; particularly bothersome are submicron lead and zinc fumes (e.g., zinc oxide fumes from 0.03 to 0.5 μm). Baghouses are usually used to control the fumes, but electrostatic precipitators are used if the gases are corrosive. If soiled scrap metal cannot be cleaned before melting, it may evolve grease or oil fumes as smoke during the heatup phase, and thus requires incineration of the smoke in an afterburner.

The practice in the BRD is to burn off oil covered chips from machining operations prior to melting.

Description of BRD technology can be found in References 53, 54, 55, 56, and 57.

Metallic aluminum is produced by the electrolytic reduction of alumina (Al_2O_3) in a bath of fused cryolite by the Hall-Heroult process with cell operating temperatures from 1 200 to 1 260 K. Toxic corrosive gases generated in the cells are hydrogen fluoride and volatilized fluorides; some fine particulates are entrained in the exit gases. Water scrubbers are used for collection of both the gases and the particulates. Some installations use baghouses with alumina-coated cloth filter bags.[58]

Secondary aluminum recovery produces particulates from the fluxes, from oily or greasy impurities in the scrap, and from chlorination of the molten aluminum. When chlorine gas is used to degas the melt or to remove magnesium, hydrogen chloride gas and aluminum chloride fume are evolved. The fume is difficult to collect because it is small and hygroscopic. Water scrubbers are used to collect the gaseous contaminants.

In the BRD, dust content in exit gases, produced in the secondary recovery of nonferrous metals, is limited to 50 mg/Nm^3.

Further description of BRD technology can be found in Reference 59.

3.3.10 Soap and Synthetic Plants

Principal sources of particulates in the making of soap and synthetic detergents are the handling of dry raw materials and the spray drying of products. Fabric filters are widely used to control dusts generated from these operations.

The wet chemical processes are relatively innocuous from the standpoint of particulates, but odorous gases and vapors are generated in some instances. Gases from the spray dryers, discharged at approximately 370 K, contain large amounts of moisture. In addition, the product is sticky at this temperature, and dry collection in fabric filters or electrostatic precipitators is difficult. Multiple cyclones can be used as precleaners, but scrubbers are used almost exclusively to collect fine dust. Moderate pressure venturi units or baffled scrubbers provide adequate control in many instances; these usually use slurries rather than water, and product is recovered from the slurries. Residual fine particles, together with high moisture levels, frequently impart marked opaqueness to the stack gases; this opaqueness can sometimes be avoided by waiting until after the spray drying to add less stable ingredients to the product.

3.3.11 Glass Furnaces and Glass Fiber Facilities

Reverberatory furnaces, used to produce nearly all glass products, generate significant quantities of particulates.

In glass furnaces, oil or natural gas is fired directly over the melt. Heat is reclaimed in checkerwork regenerators and used to preheat combustion air. Raw materials--mainly cullet (scrap glass), limestone, soda ash, Na_2SO_4, and sand--are charged at one end and molten glass is pulled from the other end. Temperatures as high as 1 760 K in the furnace are usually near 1 500 K at the point of discharge.

Particulates in exhaust gases are traceable to two principal sources: (1) unmelted raw materials entrained in combustion gases and (2) other solids (oxides of potassium, sodium, and calcium) entrained in carbon dioside gases from the melt. Losses from large furnaces range from

1 g/s to as high as 12 g/s; most units release less than 5 g/s.

Emissions are controlled through furnace design, electric heating, and raw material control rather than with stack-cleaning devices. Control with fiberglass filters is feasible, but the particulates are extremely difficult to handle. For BRD technology see Reference 60.

In the manufacture of glass fiber, both the odors and the visible particles from the forming processes are unacceptable. Direct-fired afterburners, as well as packed fiber beds, have been used successfully at curing ovens to control these emissions.[1]

3.3.12 Carbon Black Installations

Because of the extremely fine sizes (0.01 to 0.4 μm) and fluffiness of carbon black particles, they are readily emitted from improper handling and transferring.

In the furnace black process (oil and gas), which accounts for 94 percent of the total production, furnace temperature is kept at about 1 650 K, but the black-laden gases are cooled to 500 and 560 K before they enter the dust-collecting equipment. The preferred system is an agglomerator followed by a baghouse;[23] overall collection efficiency of such a system is about 99 percent. See Reference 61 for BRD technology.

3.3.13 Gypsum Processing Plants

Gypsum, the basic ingredient of plaster and wallboard, is usually manufactured in highly mechanized systems by grinding, drying, and calcining gypsum rock; these processes are principal sources of dust. Handling, packaging, and wallboard manufacture are secondary sources.

Gypsum is dryed in direct-fired dryers to remove free moisture before calcining. Exit gases of about 380 K contain a large amount of fine dust. Electrostatic precipitators, baghouses, or scrubbers are almost always used to remove this dust from exit gases.

Calcining at 480 to 500 K in externally heated kettles or conveyors produces less exit gases than the dryers do. Electrostatic precipitators have been used to control calciners, but dust collection has not always been adequate. Baghouses now find better acceptance. Most new gypsum plants are equipped with high-temperature fabric filters with heaters to prevent moisture from condensing in ductwork. Auxiliary baghouses collect dust from conveying and processing points. In most instances, a salable product is reclaimed.

3.3.14 Coffee Processing Plants

The processing of green coffee beans and the production of dehydrated instant coffee generate dust and liquid aerosols as well as odorous gases. The sources of emissions are roasters, spray dryers, waste heat boilers, and green-coffee cleaners.

Roasters are the predominant sources of oil aerosols and odors, but they also create significant amounts of solid particulates. Chaff, a flaky membrane from the bean, and other solids are collected in simple cyclones at 480 to 370 K. Remaining aerosols and odorous gases are incinerated in afterburners at 920 to 1 030 K.

Spray dryers, not unlike those used in other industries, are used to produce instant coffee. If dryers are operated properly, small amounts of fine particulate matter are generated; satisfactory dust control can be achieved with dry multiple cyclone collectors. Periodic upsets, however, can cause occasional particulate discharges; therefore, many plants operate scrubbers or baghouses downstream of mechanical collectors. Collected fines are blended with the main product stream.

Producing instant coffee generates large quantities of leached coffee grounds which are usually burned in waste heat boilers similar to coal-fired boilers. Particulate emissions depend on the type of firing and the ash content (usually about 4 percent by weight of dry grounds).

Green coffee cleaning and handling create dust and chaff which normally can be handled well in simple cyclones.

3.3.15 Cotton Ginning Plants

The major sources of particulates in cotton ginning are the gin itself and the incinerator for burning. High-efficiency multiple cyclones successfully collect the coarse particles from the ginning, and the recently developed stainless steel in-line filters are effective for the fine particles from the gin's lint cleaner. Because incineration of trash generates a large portion of the particulates released from uncontrolled ginning plants, disposal by composting, rather than incineration, is being practiced in some parts of the country.

3.4 CONSTRUCTION AND DEMOLITION ACTIVITIES

Periodically, the construction and demolition of buildings and roads create local particulate nuisance problems. Principal construction, demolition, and related dust-generating operations are:

1. Demolition of masonry.
2. Open burning of wooden structures, trees, shrubbery, and construction lumber.
3. Movement of vehicles on unpaved roads.
4. Grading of earth.
5. Handling and batching of portland cement, plaster, and similar materials at the site.
6. Sandblasting of buildings.

Techniques have been developed to minimize dust releases from most operations, but they are moderately expensive and offer little, if any, compensating monetary return.

3.4.1 Demolition of Masonry

When a brick, plaster, or concrete wall is demolished, most of the particulates are released when the broken wall hits the ground or floor. Before walls are torn down, they should be sprayed with water; and after the fall, more water should be sprayed onto the pile of debris. This technique, at best, is inefficient--it may reduce particulates by only 10 to 20 percent. In cold or freezing weather, water spraying systems become almost completely inoperable.

One concept of dust collection at demolition sites calls for enclosing the four sides of the building with plastic sheets attached to the scaffolding by removable slips and using an exhaust fan to suck air from the open top of the building into bag filters.[62] This concept is one of the few possibilities for collection of demolition dust in congested metropolitan areas.

3.4.2 Burning of Trash

Because open burning cannot be controlled adequately, the combustibles should be removed to a controlled incinerator or to a sanitary landfill.

3.4.3 Stirring of Road Dust

Trucks moving across dry, unpaved roads are a prime dust source at construction projects. Dust can be held to a tolerable level by blacktopping, oiling, or by frequent spraying with water.

3.4.4 Grading of Roads

Dust created by earthmoving equipment is less when winds are light and materials are moistened to minimize entrainment of dust in ambient air currents. Sand, rock, gravel, and the roadbed can be sprayed with water.

3.4.5 Handling of Dusty Materials

Portland cement, plaster, and similar items become easily airborne during handling and batching, especially if the materials are mixed at the site. The best solution is to mix materials in a central location, to hood all major points, and to vent the dust to a fabric filter.

3.4.6 Sandblasting of Buildings

Sandblasting creates particles that are difficult to control. When access is possible, hooding and ductwork can be provided from the point of sandblasting to a baghouse or similar high-efficiency dust collection device. A more common practice is to shroud the operator and the area and to pipe a clean air supply to the operator, but this practice is successful only when winds are light.

Sandblasting of buildings has been replaced in many areas by steam cleaning and acid washing.

3.5 SOLID WASTE DISPOSAL SITES IN THE UNITED STATES

Of the solid waste collected in 1967, 86 percent was disposed of at land disposal sites, 8 percent was burned at municipal incinerators, and only 6 percent was disposed of in sanitary landfills.[63] There are approximately 12 000 land disposal sites in this country.[63] Such sites, either privately or publicly owned, are used by public or private contractors for dumping solid wastes. Only 6 percent of these sites are sanitary landfills, with daily cover but no open burning. Three-quarters of the remaining 94 percent have some form of open burning.[63] This latter type of disposal accounts for a large share of the particulate emissions estimated to arise from the burning of solid wastes and causes emissions which most frequently spur complaints by citizens.[64] Particulates from incineration cause soiling, reduced visibility, and a smoky appearance of the air.

Some amounts of construction, institutional, industrial, and agricultural waste are also burned. Field burning to remove weeds or residue, incineration of wood waste, and burning of car bodies for salvage contribute significantly to local and even regional air pollution problems; in some areas of the country, these sources may, in fact, be the greatest cause of particulate air pollution.

Solid waste is grouped into five categories:[65]

1. Residential and commercial solid waste includes food waste, paper, plastics, metals, cloth, wood, and many other materials.
2. Construction and demolition waste includes building materials such as wood, steel, plaster, brick, and concrete.
3. Institutional solid waste from hospitals, nursing homes, and other institutions is similar to residential and commercial solid waste but may contain pathogenic materials.
4. Industrial solid waste includes a variety of combustible and noncombustible materials.
5. Agricultural waste includes animal droppings and crop residue, but excludes stands of timber or brush burned in accidental forest fires.

In the United States, 2.5 kg/day per person of refuse and garbage is collected. Other forms of solid waste--i.e., industrial wastes and other material disposed of by local uncontrolled incineration--amount to at least 2 kg/day per person.[1]

One survey indicates that if present trends continue and long-range plans are not implemented, the United States will not have the capability to handle the increased amount of solid wastes generated in 1975.[66] Better engineering and planning (perhaps on a regional basis) and use of existing technology, specifically in the fields of incineration and sanitary landfill operation, are the keys to mastering the problem of air pollution from solid waste disposal.

3.5.1 Disposal Without Incineration

Disposal and volume-reduction methods that do not use incineration are most desirable from an air pollution standpoint, and in many cases, they are more economical and more acceptable to a community.

3.5.1.1 Sanitary Landfill--The sanitary landfill, not to be confused with an open dump, is an acceptable means of solid waste disposal.[67] Almost any kind of solid waste can be disposed of without open burning by systematically dumping it on the ground or into trenches, compacting it by driving a bulldozer or other heavy equipment over it, and covering it at the end of each day with a layer of compacted earth to prevent rodent and insect infestation and to confine odors. When completely filled, land so used may be made into parks and recreation areas. Emissions are limited to materials entrained in the air by earthmoving equipment; these emissions can be minimized by wetting the fill material.

Choice of a site and method of operation of a sanitary landfill are primarily dependent on the topography and availability of land, but other factors such as length of haul, land drainage, source of cover material, and quantity and cost of land needed to handle future waste generation must also be considered.

1. Land requirements. Normally, sites are selected for 10- to 20-year periods. About 1 200 m^3 of land is required per 1 000 persons per year of operation when the waste production is 2 kg/day per person.[68] Cover material, at least 20 percent by volume of the compacted waste, may be supplied from the site or transported from nearby sites.
2. Topography. Depressed areas, such as ravines and abandoned pits, are usually desirable sites, but flat land can be used by applying progressive excavation or the cut-and-cover method.[67]
3. Operation. Continuous use of heavy earthmoving equipment is required to compact and cover the waste with no less than 150-mm of fill material at least once a day. An intermediate 800-mm layer of cover material is usually spread over completed sections. A final 600-mm cover is a minimum for the entire site on completion of the operation.
4. Cost. Costs of site, site preparation, and operation must be computed; and the final value of the land when reclaimed must be balanced against the initial costs of the land. Equipment and operating costs usually range from $0.88 to $1.65 per 1 000 kg of solid waste placed in the landfill.[69] (Transportation cost to the site is not included in this figure.)

3.5.1.2 Composting--Composting, as applied to waste disposal, is the biological decomposition of the organic components of waste. Stable organic residue, the ultimate product, is usable as low-grade soil conditioner. The market for compost, however, has not been good because equivalent commercial products are less costly.

Because composting costs are the same or higher than those of incineration, only a few plants are operating in the United States today.[70] Composting could be a suitable method for handling organic waste with little or no particulate air pollution, where commercial fertilizer is not readily available and the scrap market is good. Odor problems, however, must be managed.

3.5.1.3 Shredding--Disposal of bulky waste can be facilitated by shredding. Auto tires, for instance, can be shredded and placed in a sanitary landfill instead of being burned. Bulky wood waste, such as driftwood and combustible demolition waste, has heretofore been burned openly, but it can be shredded and burned in a controlled incinerator if it is mixed with refuse so that it does not blind the grates.

Each year, more than 6 million automobiles are junked in the United States. Automobile body disposal, therefore, is one of the growing bulky solid waste problems. The most promising solution appears to be to step up the reuse of metal scrap in the domestic steel and foundry industries. Burning of automobile bodies is apparently required to remove upholstery, grease, and paint and to produce a competitive scrap. Open burning is unacceptable; it releases large quantities of particulates containing cadmium, nickel, and lead. Open burning has been replaced by controlled incineration.[71] Unfortunately, however, because of the low market price for automobile scrap, the cost of controlled incineration is often prohibitive.

Shredding followed by a series of mechanical separations to remove contaminants can produce a relatively usable scrap with little or no incineration.[72] However, the low market price for shredded scrap restricts the area from which shredders can draw junk automobiles. Flattening junk autos and delivering them for outlying areas to a centralized shredder may be necessary to improve the economics of this operation.

3.5.1.4 Compaction--Compaction, although not a disposal method, reduces refuse volume so that large storage areas are not required and so that transfer to landfills or municipal incinerators is easier.

In compaction installations, refuse is charged through a door on each floor of a building; and when refuse collects in a receiving hopper, it is forced by hydraulic ram into a metal container with a capacity up to 1.5 m^3. Compaction of refuse in the storage container is usually 3:1; however, much higher compaction ratios can be obtained.

Widespread use of compaction rather than, say, incineration could overload pickup and disposal facilities and could cause an accumulation of refuse if scheduled pickup is prevented.

3.5.2 Disposal With Incineration

Incineration may be justified in areas where land for sanitary landfill is scarce or hauling costs are prohibitive. Well-designed and well-operated equipment to minimize the discharge of particulates is of utmost importance in the use of incinerators.

Emissions of particulates from combustion of solid waste, including open burning, can range from 1.5 to 15 kg/1 000 kg of waste, depending on the degree of combustion and control.[1] Reduction of these emissions to the desired level requires either that the incinerator be designed for control of fly ash or that a separate control system be used. Table 3-10 summarizes the collection efficiencies of various control devices applied to incinerators.

BRD technology for disposal by incineration is described in References 73, 74, and 75.

Table 3-10. - COLLECTION EFFICIENCIES FOR VARIOUS TYPES OF MUNICIPAL INCINERATION PARTICULATE CONTROL SYSTEMS[1]

Type of system	Efficiency, %
Settling chamber	0 to 30
Settling chamber and water spray	30 to 60
Wetted baffles	60
Mechanical collector	30 to 80
Scrubber	80 to 95
Electrostatic precipitator	90 to 96
Fabric filter	97 to 99

3.5.2.1 Open Burning--The results of the National Solid Wastes Survey show that open burning is widespread. Eighty-six percent of solid waste collected in 1967 went into land disposal sites, 75 percent of which resulted in some form of open burning.[63] Every effort should be made to substitute controlled incineration or other means of disposal for open burning.

3.5.2.2 Open Top Incinerators--A refractory-lined rectangular chamber with an open top and forced overfire air has been used to incinerate a variety of wastes including liquids, solids with high caloric value,[76] general trash, and municipal refuse. This design, because of its relatively low cost, has been used for waste disposal by both municipalities and industries.

Excessive particulate emissions sometimes occur but can be avoided for a low-ash (0.5 percent by weight) material incinerated under carefully controlled conditions.[77] Full-scale units have been used to burn certain high heat value, low-ash wastes without visible emissions of smoke; but before applying this technique, the ash content and physical characteristics of the waste should be tested. Control of charging and airflow is required to prevent the emission of smoke and excessive fly ash, and appropriate instrumentation should be provided to ensure operation within air pollution limits.

3.5.2.3 Conical Metal Burners--Conical metal burners are used in the lumber industry to incinerate wood wastes. This single-chamber incinerator is not properly designed to minimize atmospheric emissions and is usually not operated or maintained properly. Consequently, large amounts of particulates are emitted. Some areas of the country have banned new construction of these burners.

3.5.2.4 Domestic Incinerators--Domestic incinerators may be single chamber backyard units without auxiliary fuel or dual chamber units with afterburner sections.

Many air pollution control agencies have banned backyard incinerators; a few agencies have prohibited some or all types of domestic incinerators because they fail to meet local emission standards for particulates, organic compounds, or odors. Excessive emissions are caused by improper operation and by operating without gas burners.

3.5.2.5 Commercial and Industrial Incinerators--Commercial and industrial incinerators can burn from 25 to several thousand kilograms of refuse an hour. In a single chamber unit, admission, combustion, and exhaust take place in one chamber. The multiple chamber incinerator has separate chambers for admission and combustion of the solid refuse, mixing, and further combustion of the fly ash.

Single chamber incinerators are generally inadequate to meet emission regulations; particulate emissions have been as much as 7.5 kg/1 000 kg of refuse burned.[1] Multiple-chamber incinerators, when designed, operated, and maintained properly, reduce the volume of refuse and reduce particulate emissions to as little as 2 kg/1 000 kg.[1] Even well-designed multiple chamber incinerators may require scrubbers to meet future requirements; such scrubbers must have at least 125 N/m^2 of water pressure drop and a water rate of 0.3 m^3 of water per m^3/s flue gas rate to meet emission standards for federal facilities.[78]

To keep particulate emissions to a minimum, design standards for any incinerator must satisfy the following criteria:[79]

1. Air and fuel must be in proper proportion and mixed adequately.
2. Temperature must be sufficient for combustion of solid fuel and gaseous products.

3. Retention time and temperature must be adequate for complete combustion of wastes.

Design criteria and operating practices for general refuse incinerators also apply to units burning pathological waste, but several criteria for these are more specific:

1. Preheating should precede charging of waste.
2. Flame should cover all waste in the primary chamber.
3. Gas burner rates should be sufficient to maintain at least 1 030 K in the secondary chamber.

Many air pollution control agencies review all plans for future incinerator installations to ensure that these units meet emission standards. Details that are usually checked include:

1. Plot plans, to see if unit is located in a suitable area.
2. Unit capacity, to see if it is adequate for the expected daily waste generation.
3. Gas burner placement and fuel rates, to ensure efficient combustion.
4. Scrubber waterflow rate, for design adequacy.
5. Construction materials, for resistance to heat, stress, and corrosion.
6. Air port sizes, for capacity.

Recognizing that emissions from incinerators are, to a great extent, a function of operation, some air pollution control agencies conduct training courses and publish literature to be used by incinerator operators or their supervisors. Operators can greatly reduce particulate emissions by periodic cleaning and adjustment of burners, spray nozzles, fans, and other appurtenant devices.

3.5.2.6 Apartment House Incinerators--Apartment house incinerators are important urban sources of smoke and fly ash. Emissions are usually higher than those from other incineration systems because of low combustion temperatures and improper air supply.

In the most common apartment house incinerator--the flue-fed or single flue, single chamber model--refuse is charged down the same passage through which the products of combustion leave the unit. Refuse dropped onto the fuel bed during burning smothers the fire and causes incomplete combustion. Improvements in design have produced chute-fed, multiple-chamber incinerators with separate passages for the refuse and products of combustion, but emissions still exceed most standards. Inherent in the design of flue- or chute-fed models is the high natural draft in the flues of a tall apartment building; this is a major cause of excessive particulate emissions.

Air pollution agencies have approached the control of these units in different ways. New York has prohibited the installation of new apartment house incinerators and has issued specific criteria for upgrading existing units. Washington, D.C., and Atlanta do not allow flue- or chute-fed units to be installed. Detroit and Philadelphia have set emission standards at a level that requires efficient collection equipment, usually water scrubbers.

In upgrading existing units and designing new units, several techniques are used to overcome the problems of excessive emissions: (1) A gate at the base of the charging chute prevents refuse from entering the incinerator during burning and prevents the products of combustion from leaving through the charging flue. (The gate is preferable to locking the hopper doors because these locks eventually either fail or are broken by vandals.) A bypass or separate flue must be constructed for the products of combustion in a single-flue unit. (2) Auxiliary burners placed in the primary or secondary chamber(s) increase temperature and improve combustion.[80] (3) Draft control reduces entrainment by decreasing the amount of incoming air when a preset draft level is exceeded. (4) Gas scrubbers which increase the velocity of the gases and the closeness of contact with low-velocity water are preferred over spray nozzle units which become plugged and reduce collection efficiency. (5) Definite burning periods or cycles designed according to the relative size of the apartment house and incinerator prevent overloading and minimize smoldering by systematically destroying all waste charged during any one cycle. The above techniques should reduce emissions to a level of 0.5 to 4 kg/1 000 kg of refuse burned.[1]

3.5.2.7 Municipal Incinerators--Municipal incinerators may be either batch fed or continuously fed. Continuously fed units are preferable because operating parameters, such as combustion chamber temperatures that affect particulate emissions, can be closely controlled. Grates must be designed to ensure complete burnout of material and, at the same time, to mix or tumble the refuse gently to minimize entrainment of material in the exhaust gas.

Most U.S. municipal incinerators are the refractory-lined, furnace type. Waterwall furnaces, which are more common in Europe, offer the advantage of steam generation, heat recovery, and thus lower flue gas temperatures than those of refractory-lined units; lower flue gas temperatures cause small flue gas volumes and thus require less costly control equipment. Waterwall units also require less excess air and thus have still smaller stack gas volumes.

Most U.S. municipal incinerators are equipped with some form of fly ash control system. Generally, this system is a simple, baffle-type spray chamber which prevents hot cinders and large particles, but not finer material, from being emitted. More efficient collection devices are required to meet reasonable control codes. The medium pressure drop (1.5 kN/m^2) scrubber and the electrostatic precipitator are two devices capable of effective particulate control. High-efficiency scrubbers might control emissions of potentially odorous, toxic gases. Collection efficiencies of over 95 percent can be achieved with these methods.[1]

In the BRD, offgases from municipal incinerators must not exceed 100 mg/Nm^3 of HCl in incinerators with capacities larger than 0.4 kg/s.

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4. CONTROL TECHNIQUES

Techniques for controlling particulate air pollution from stationary combustion sources may be broadly categorized as follows: source shutdown, energy substitution, energy conservation, good practice, and gas cleaning. Of these techniques, gas cleaning is by far the most important. Although they are not control techniques, source relocation and tall stacks may be used to aid in the dispersion of particulate air pollutants. The major coverage of this chapter is of methods for gas cleaning; the other techniques are covered briefly in several introductory paragraphs.

Source shutdown is a drastic control technique, but it should not be completely disregarded when particulate levels threaten the public health in emergency episodes or when lawful orders to abate are ignored.

Energy substitution involves replacing an undesirable energy source with one that generates less pollution. Energy sources used to generate power are shown in Table 4-1. When comparing energy sources, allowance should be made for differences in heat requirements between seemingly identical applications. For example, fossil fuel requirements and electrical heat requirements for space heating are likely to differ because electrically heated buildings are often insulated better than fossil fuel heated buildings. Energy sources for low and high capacity heat production are shown in Tables 4-2 and 4-3. Energy substitution can be an effective, useful technique; it has special value for control of low capacity sources when the cost of effective gas-cleaning equipment would be excessive.

Table 4-1. - COMPARISON OF ENERGY SUBSTITUTION ALTERNATIVES FOR ELECTRIC POWER GENERATION

Energy substitution alternative	Particulate emissions, ng/J input[a]
Hydroelectric	0
Nuclear	0
Gas (no control)	8.2
Oil (no control)	28.9
Coal—90 percent fly ash removal	276.8
Coal--99.5 percent fly ash removal	12.4

[a] Based on emission factors in Table 5-1 and the following gross heating values: coal, 27.91 MJ/kg (10 percent ash); oil, 41.81 GJ/m^3; gas, 37.3 MJ/m^3.

Table 4-2. - COMPARISON OF ENERGY SUBSTITUTION ALTERNATIVES FOR STATIONARY COMBUSTION SOURCES OF LESS THAN 2.93 MJ/s INPUT

Energy substitution alternative	Particulate emission equivalent,[a] ng/J useful heat
Electric heat (hydrolectric or nuclear power plant originated)	0
Electric heat (gas-fired power plant originated)	20.7
Electric heat (oil-fired power plant originated)	90.9
Electric heat (coal-fired power plant originated--90 percent fly ash removal)	826.3
Electric heat (coal-fired power plant originated--99.5 percent fly ash removal)	41.3
Gas-fired furnace on site (no control)	12.4
Oil-fired furnace on site (no control)	33.1
Coal-fired furnace on site (no control)	458.7

[a] Based on emission factors, Table 5-1; on gross heating values (coal, 27.9 MJ/kg at 10 percent ash; oil, 38.9 GJ/m^3; gas, 37.3 MJ/m^3); and on estimated thermal efficiency of on-site heating systems (electric, 100%, coal, gas, and oil 75%).

Table 4-3. - COMPARISON OF ENERGY SUBSTITUTION ALTERNATIVES FOR STATIONARY COMBUSTION SOURCES OF 2.93 TO 29.3 MJ/s INPUT

Energy substitution alternative	Particulate emission equivalent,[a] ng/J useful heat
Electric heat (hydroelectric or nuclear power plant originated)	0
Electric heat (gas-fired power plant originated)	20.7
Electric heat (oil-fired power plant originated)	90.9
Electric heat (coal-fired power plant originated--90 percent fly ash removal)	826.3
Electric heat (coal-fired power plant originated--99.5 percent fly ash removal)	41.3
Gas-fired furnace on site (no control)	12.4
Distillate oil-fired furnace on site (no control)	57.8
Residual oil-fired furnace on site (no control)	82.6
Stoker-fired furnace on site (no control)	1 148.6
Stoker-fired furnace on site (90 percent fly ash removal)	115.7
Stoker-fired furnace on site (99.5 percent fly ash removal)	4.1

[a] Based on:
1. Emission factors--Table 5-1.
2. Fuel properties:
    Heating value, coal--27.91 MJ/kg
    Heating value, distillate oil--38.9 GJ/m^3
    Heating value, residual oil--41.81 GJ/m^3
    Heating value, gas--37.3 MJ/m^3.
3. Estimated thermal efficiency of on-site heating systems:
    Electric--100 percent
    Coal, gas, oil--75 percent.

Energy conservation reduces particulate emissions by reducing fuel consumption. Tables 4-4 and 4-5 show average national trends in efficiency improvements--primarily, the use of higher temperatures and pressures--for steam electric power generating plants. Processes now under development (e.g., the magnetohydrodynamic, electrogasdynamic, and fuel cell) have promise of improving efficiency even more than heretofore achieved. Energy conservation may not appear to be economical when compared with other control techniques.

Equipment must be properly selected, installed, and operated to minimize emissions of particulates. Guidelines for good practice are published by fuel industries, equipment manufacturers, engineering associations, and government agencies.

In the selection of combustion systems, proper attention should be given to load requirements; that is, components of the system should be compatible and operated within design limits to avoid excessive discharge of particulates. Each component--the fuel-handling system, the draft system, the fuel-burning system, the flues and stacks, the ash-handling system, and the controls--must be selected and integrated to handle the load and the fuel to be burned. Therefore, it is necessary for the load to be accurately estimated, for the design capacity of the system to be sufficient to carry the maximum load, and for consideration to be given to future increases in load requirements. The minimum design capacity of one unit of the combustion system should be sufficient to carry the minimum load requirements of the facility, and the total combustion system should be selected to carry any load between maximum and minimum.

Table 4-4. - CONSUMPTION OF FUELS BY ELECTRIC UTILITIES IN THE UNITED STATES, 1955 TO 1969[1]

Year	Consumption per GJ		
	Coal, kg	Oil, m^3	Gas, m^3
1955	120	0.089	95
1960	111	0.082	86
1965	108	0.078	83
1968	109	0.079	81
1969	111	0.081	82

Table 4-5. - CONSUMPTION OF FUELS BY ELECTRIC UTILITIES IN THE BRD, 1955 TO 1970[2]

Year	Consumption per GJ			
	Raw lignite, kg	Bituminous coal, kg	Oil, kg	Natural gas, Nm^3
1955	500	136	95	0.447
1960	420	113	79	0.373
1965	375	101	71	0.334
1970	350	95	67	0.313
Gross calorific value	8 MJ/kg	31.4 MJ/kg	42 MJ/kg	32 MJ/kg

Properly installed equipment will promote clean, efficient operation. Comprehensive installation instructions and plans are prerequisites. The designer of the entire system and the manufacturers of its components provide such plans and instructions. Only qualified personnel should install equipment, and all work should be inspected periodically.

Proper operation and maintenance of equipment will reduce particulates. Stationary combustion units should be operated according to the recommendations of either the manufacturer or another authority at all times. Sensitive monitoring systems are helpful in indicating needed repair; if such attention is indicated, it should be promptly provided. If proper operations are disregarded, storage pile fires and fuel- and ash-handling systems can become significant sources of particulate air pollution.

Source relocation will not eliminate particulate emissions from a stationary combustion source, but it will eliminate emissions from the original location of the source. Due consideration should be given, however, to possible air pollution effects on other areas. Source relocation is ordinarily considered when a new plant is to be built to replace one that has created air pollution problems.

Gas cleaning is the most common technique used for control of particulates from stationary combustion sources. Table 4-6 shows the optimum performance expected from the various types of gas-cleaning systems used for removing particulates from flue gases. Selection of commercially available gas-cleaning equipment for various applications is based on particle characteristics (Fig. 4-1), carrier gas characteristics, and on process operating, design, and economic factors.

Table 4-6. - OPTIMUM EXPECTED PERFORMANCE OF VARIOUS TYPES OF GAS-CLEANING SYSTEMS FOR STATIONARY COMBUSTION SOURCES

Sources	Removal of uncontrolled particulate emissions, percent						
	Systems in operation				Systems under development		
	Settling chambers	Large-diameter cyclones	Small-diameter cyclones	Electro-static precipi-tators	Stack sprays	2 kN/m^2 pressure drop scrubbers	Fabric filters
Coal-fired:							
Spreader, chain grate, and vibrating stokers	50[a]	60[a]	85[a]	99.5[c]	60[e]	99+[g]	99.5[h]
Other stokers	60[a]	65[a]	90[a]	99.5[c]	80[e]	99+[g]	99.5[h]
Cyclone furnaces	10[a]	15[a]	70[a]	99.5[c]	([f])	([f])	([f])
Other pulverized coal units	20[a]	30[a]	80[a]	99.5[c]	([f])	99+[g]	99.5[h]
Oil-fired	5[b]	10[b]	30[b]	75.0[d]	([f])	([f])	([f])

[a] Estimate based on References 3 and 4.

[b] Efficiency estimated--not commonly used.

[c] Estimate based on Reference 5.

[d] Estimate based on private reports of field experience.

[e] Reference 6.

[f] Insufficient data for estimate.

[g] Estimate based on Reference 7.

[h] Estimate based on Reference 8.

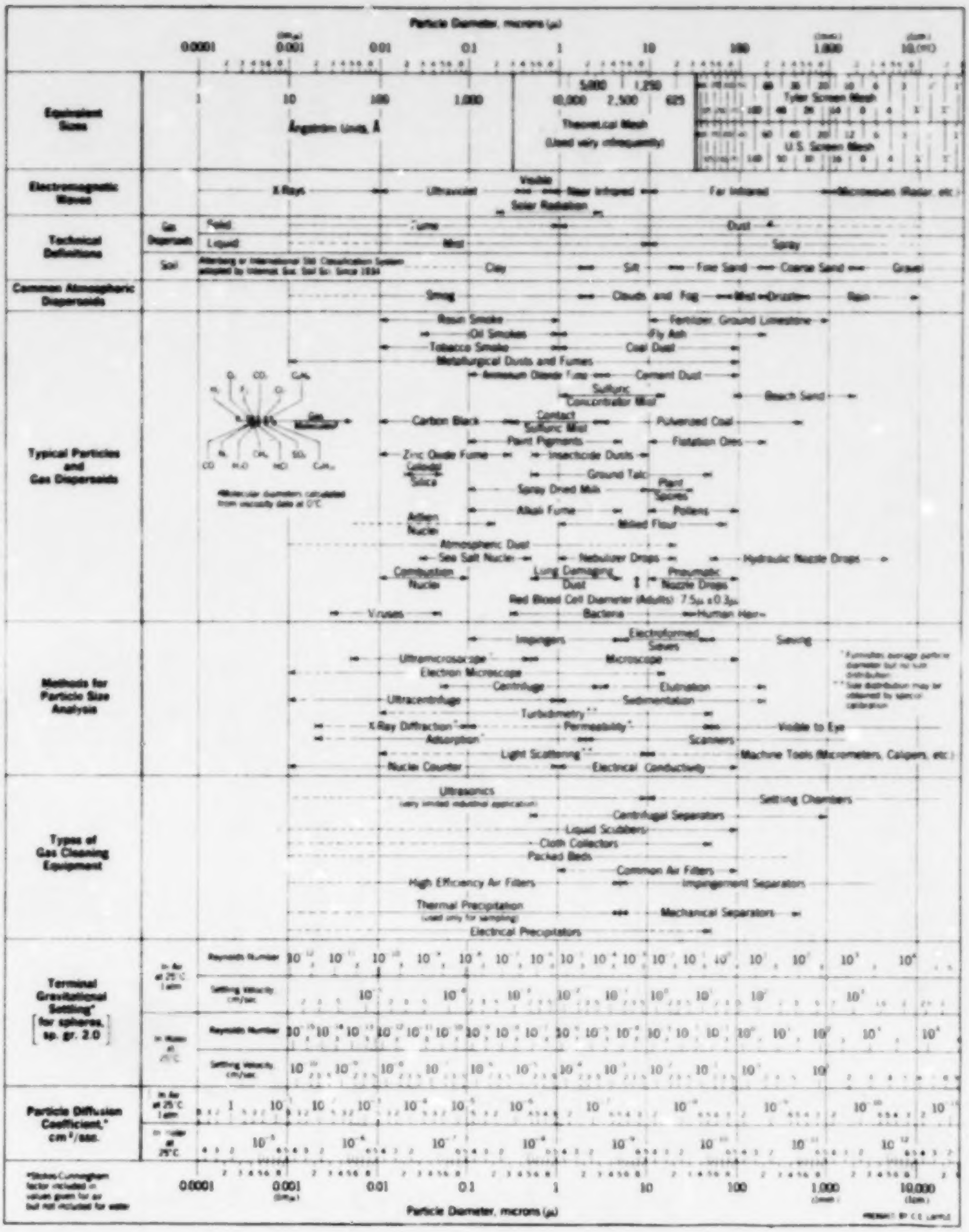


Fig. 4-1. Characteristics of particles and particle dispersoids.[9]

Information on the various gas-cleaning devices presented in this section includes:

1. Introductory material: definitions.
2. Equipment description: design variations, arrangements, and performance.
3. Operational factors: power requirements, pressure drops, temperature limitations, maintenance and disposal problems.
4. Applications: specific processes and efficiencies.

Capital installation, and operating costs for the devices--settling chambers, cyclones, scrubbers, electrostatic precipitators, fabric filters, and afterburners--are discussed in Section 6.

4.1 SETTLING CHAMBERS

Gravitational settling chambers use the force of gravity to separate dusts and mists from gas streams. The chambers are simple in design and operation but have large space requirements and low collection efficiencies for small particles. Typically, settling chambers are used as precleaners in conjunction with other, more efficient, control equipment.

4.1.1 Description of Equipment

In a gravitational settling chamber, the velocity of the carrier gas is decreased so that particles in the gas settle out by gravity. Velocity is decreased by expanding the ducting into the chamber. The chamber may be either a simple balloon duct (Fig. 4-2), an expansion chamber with a dust hopper (Fig. 4-3), a dust-settling chamber (Fig. 4-4), or a multiple-tray dust collector (Fig. 4-5). A multiple-tray dust collector increases collection efficiency by reducing the vertical settling distance; distance between trays may be as little as 0.025 m.

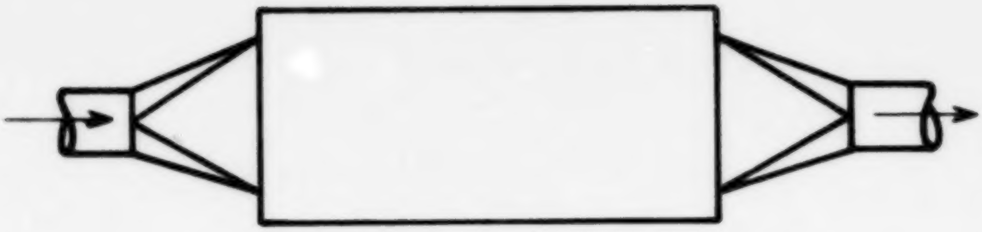


Fig. 4-2. Balloon duct.

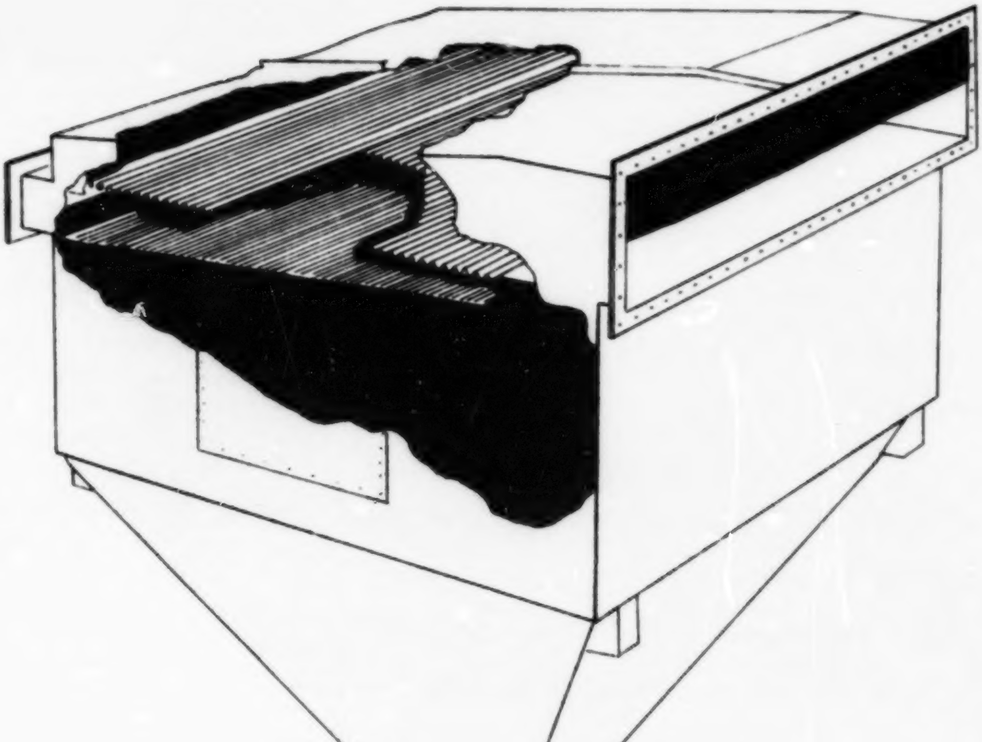


Fig. 4-3. Baffled expansion chamber with dust hopper.

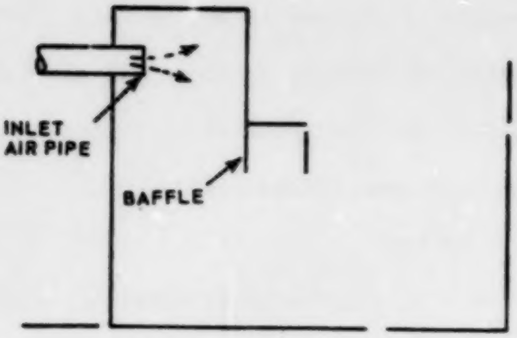

INLET
AIR PIPE
BAFFLE

Fig. 4-4. Dust settling chamber.

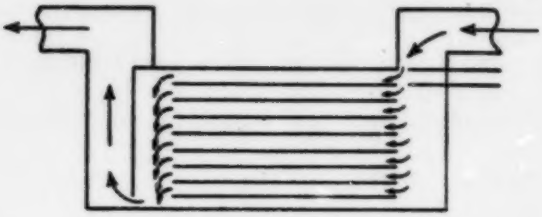


Fig. 4-5. Multiple-tray dust collector.

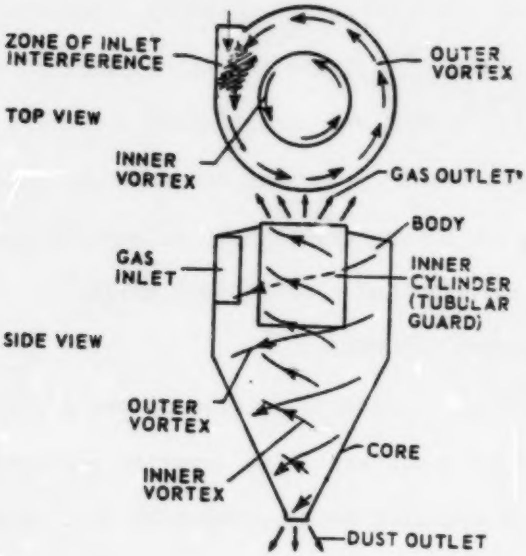

ZONE OF INLET
INTERFERENCE
TOP VIEW
OUTER
VORTEX
INNER
VORTEX
GAS OUTLET
BODY
GAS
INLET
INNER
CYLINDER
(TUBULAR
GUARD)
SIDE VIEW
OUTER
VORTEX
CORE
INNER
VORTEX
DUST OUTLET

Fig. 4-6. Conventional reverse-flow cyclone.

Vertical distribution of the gas is not critical, but the gas must be uniformly, laterally distributed as it enters the chamber; uniform distribution is achieved by using gradual transition, guide vanes, distributor screens, or perforated plates.

4.1.2 Operational Factors

Because the settling rate of dust decreases with increasing turbulence of the gas, the velocity of the gas stream is usually kept as low as possible. It must not be so great that settling particles are reentrained or so low that equipment size is excessive. Normally from 0.3 to 3 m/s, the gas velocities are based on experience or on tests conducted under actual conditions since particulate settling rates may be influenced by factors such as agglomeration and electrostatic charge.

4.1.3 Typical Applications

Settling chambers are usually installed as precleaners to remove large particles and agglomerated particles which can clog small diameter cyclones and other dust-cleaning equipment. Because of space requirements, they are usually designed to collect particles larger than 43 μm (325 mesh)[10] and are thus not satisfactory for total particulate control.

Dust-settling chambers, having low pressure drops, are frequently used on natural draft exhausts from kilns and furnaces.[11] Other applications are cotton gins and alfalfa feed mills.[12]

4.2 DRY CENTRIFUGAL COLLECTORS

Dry centrifugal collectors (cyclones) use centrifugal force created by a spinning gas stream to separate particulates from the carrier gas. The spinning motion, imparted by a tangential gas inlet by vanes or by a fan, forces the inert dust particles outward to the separator wall from which they fall into a receiver.[13]

Three forces that act on individual dust particles during the separation process are gravitational, centrifugal, and frictional drag. By assuming that particles respond conventionally to these forces, cyclone performance can be estimated.[14,15]

4.2.1 Description of Equipment

Centrifugal collectors are either conventional reverse-flow cyclones (tangential inlet or axial inlet), straight-through-flow cyclones, or impeller collectors. In a conventional reverse-flow cyclone with a tangential inlet (Fig. 4-6), the dust-laden gas flows in a helical path that reverses at the base of the cyclone to form an inner core and the dust particles forced to the wall by centrifugal action drop to the bottom. Dust must be removed without disturbing the gas flow; any disruption reduces collection efficiency and causes particle reentrainment. A conventional cyclone with an axial inlet is illustrated in Fig. 4-7.

In a straight-through-flow cyclone (Fig. 4-8), particulates are collected from the periphery of the base and fled off to a secondary collector, either a cyclone or a settling chamber. This type of cyclone is used frequently as a fly ash collector and as a precleaner (skimmer) for other types of dust-cleaning equipment. Its chief advantages are low pressure drop and high gas-handling capacity.

In the impeller collector (Fig. 4-9), the dust-laden gas enters the throat of the impeller and passes through a specially shaped fan blade which throws it into an annular slot leading to the collection hopper. The principal advantage is its compactness, which is important for a plant requiring a large number of collectors. The major disadvantages are plugging and rotor imbalance resulting from the buildup of solids on

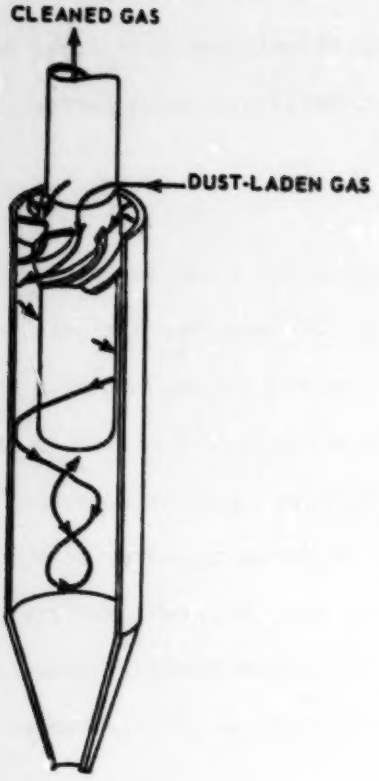

CLEANED GAS
DUST-LADEN GAS

Fig. 4-7. Axial inlet cyclone.

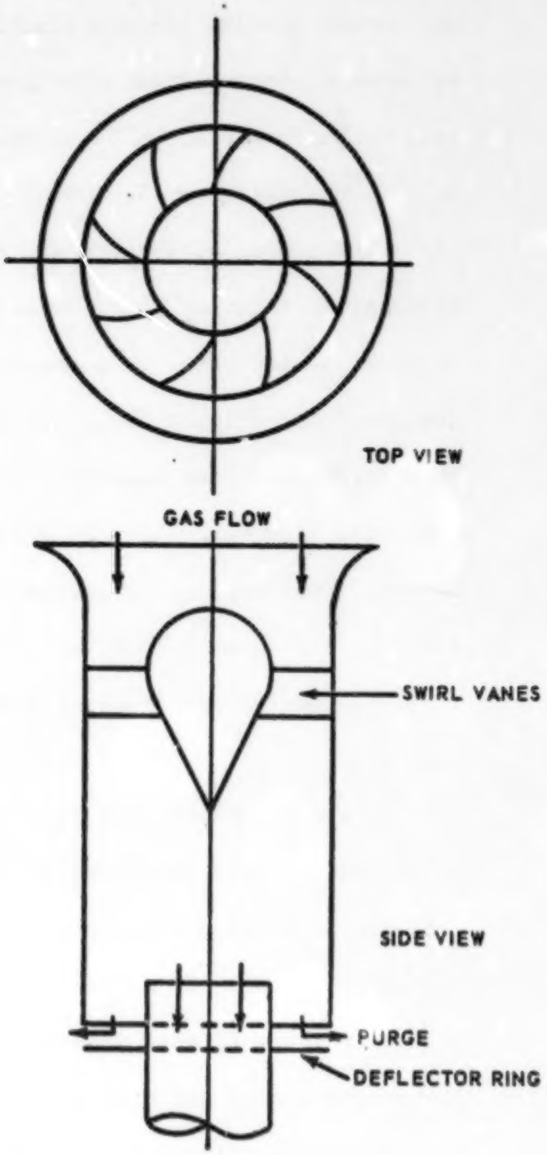

TOP VIEW
GAS FLOW
SWIRL VANES
SIDE VIEW
PURGE
DEFLECTOR RING

Fig. 4-8. Straight-through-flow cyclone.

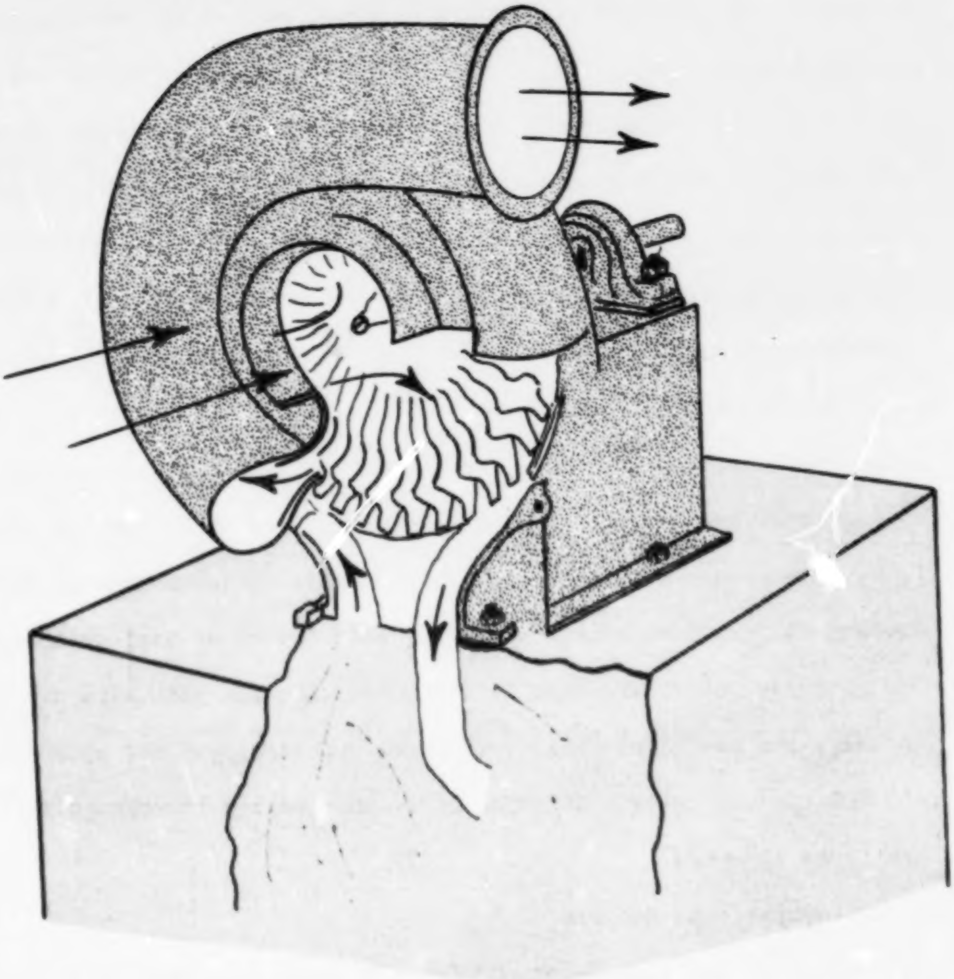


Fig. 4-9. Dynamic cyclone showing method by which dust is dynamically precipitated and delivered to the storage hopper.

the rotating impeller and temperature limitations resulting from the bearings and seals in the device.

A recent design modification is the double head-cut cones type collector in which the outer wall of the cyclone is mechanically rotated to avoid the usual low gas velocity adjacent to a stationary wall.[16] A mechanical modification which permits withdrawal of the boundary layer can increase collection efficiency at no increase in pressure drop.[17] In the rotary flow collector (Fig. 4-10) a downward potential flow is delayed by a reversed and continued as a rotary flow upward. The potential flow is caused by tangential nozzles that are inclined downward and generate the rotation of the feed gas. A part of the potential flow carrying the particles is withdrawn from the collecting device. In contrast to cyclones, rotary flow collectors have no friction at the chamber wall.

Another type of centrifugal collector used in the BRD is the Petersen pressure-drop separator (Fig. 4-11). This collecting device divides the gas flow into a number of thin layers of high velocity. The thin gas layers are then deflected so that the particles are forced to leave the gas flow. The centrifugal accelerations are approximately 100 000 times gravity. In order to avoid clogging the channels, liquor has to be injected.

4.2.2 Operational Factors

Conventional well-designed, large diameter cyclones provide high collection efficiency for particles from 40 to 50 µm and typically have a cut size of 8 µm[18] (at which overflow and underflow concentrations are equal); those with smaller diameters (less than 0.31 µm) operate efficiently for particles of 15 to 20 µm and have cut sizes of 3 µm.

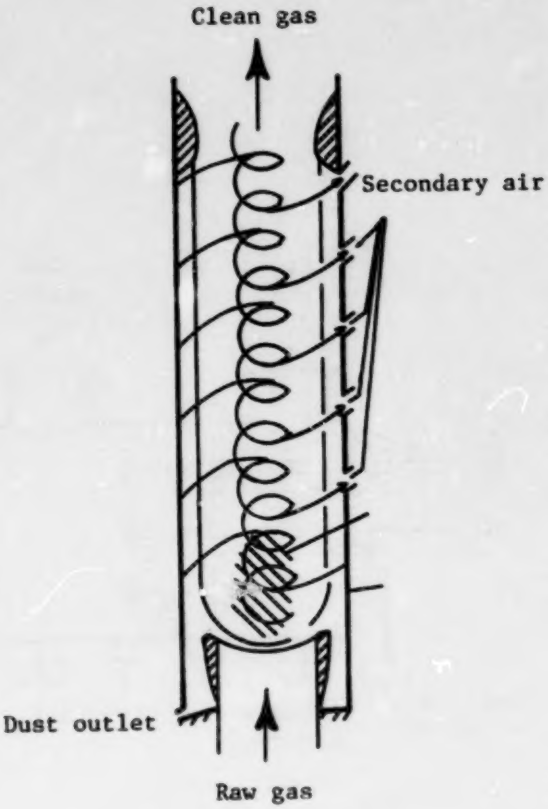

Clean gas
Secondary air
Dust outlet
Raw gas

Fig. 4-10. Siemens rotary-flow collector.

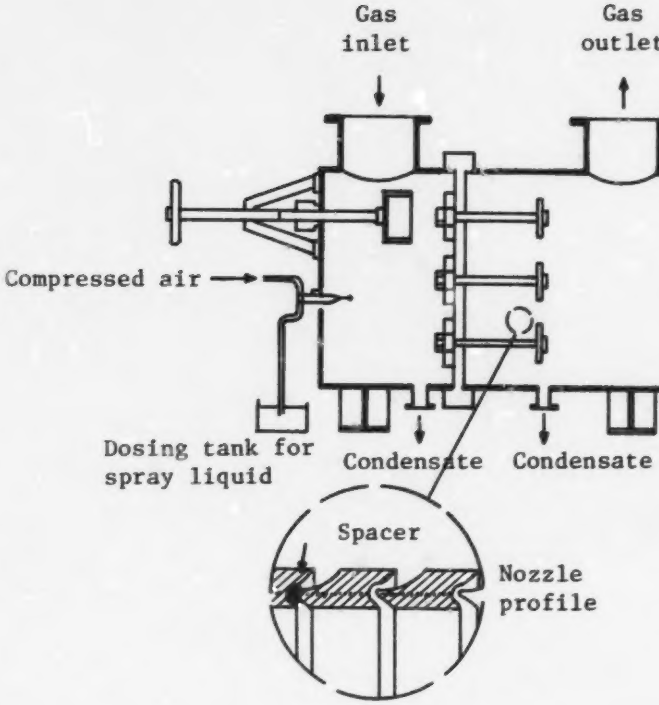

Gas inlet
Gas outlet
Compressed air
Dosing tank for spray liquid
Condensate
Condensate
Spacer
Nozzle profile

Fig. 4-11. Petersen pressure-drop separator.

Efficiencies for various particle size ranges are shown in Table 4-7. Fig. 4-12 compares the efficiency of small and large diameter cyclones over a range of particle sizes.

Collection efficiency of a small diameter cyclone is low if much of the suspended particles average less than 5 μm. In special cases (i.e., with a high tendency to agglomerate or with concentrations over 228 g/m^3), cyclones remove dust particles smaller than 5 μm. Efficiencies as high as 98 percent have been attained on agglomerated dusts having original particle sizes from 0.1 to 2.0 μm.[19]

Causes of reductions in collection efficiency include the infiltration of air at the bottom of the cyclone and the buildup of dust on the cyclone walls. The buildup may be reduced by vibrators and flexible rubber cones.[20] Special valves may be used to discharge dust without admitting air. Typical dust removal methods are illustrated in Fig. 4-13.

The pressure drop across a cyclone, which depends on a number of variables, usually ranges from 249 to 1 990 N/m^2 and increases with increasing inlet velocity. Efficiency also increases with increasing velocity but with a weaker dependence than pressure drop.[21] For a given cyclone-dust combination, an optimum velocity exists which strikes the best balance between turbulence and centrifugal separation. Pressure drop is caused by frictional losses and kinetic effects. Friction losses depend on surface roughness, gas velocity, and the physical properties of the gas and aerosol, whereas kinetic effects result from acceleration of the gas stream. The pressure drop through a cyclone can be reduced either by reducing the rotational velocity (less acceleration and lower spearation efficiency) or be decelerating the gas stream before discharge to recover a portion of the rotational kinetic energy. In the impeller collector,

Table 4-7. - RELATIONSHIP BETWEEN PARTICLE SIZE AND CYCLONE EFFICIENCY RANGE[17]

Particle size range, µm	Conventional cyclone efficiency	High cyclone efficiency
Less than 5	------	Low
5 to 20	Low	Medium
15 to 50	Medium	High
Greater than 40	High	High

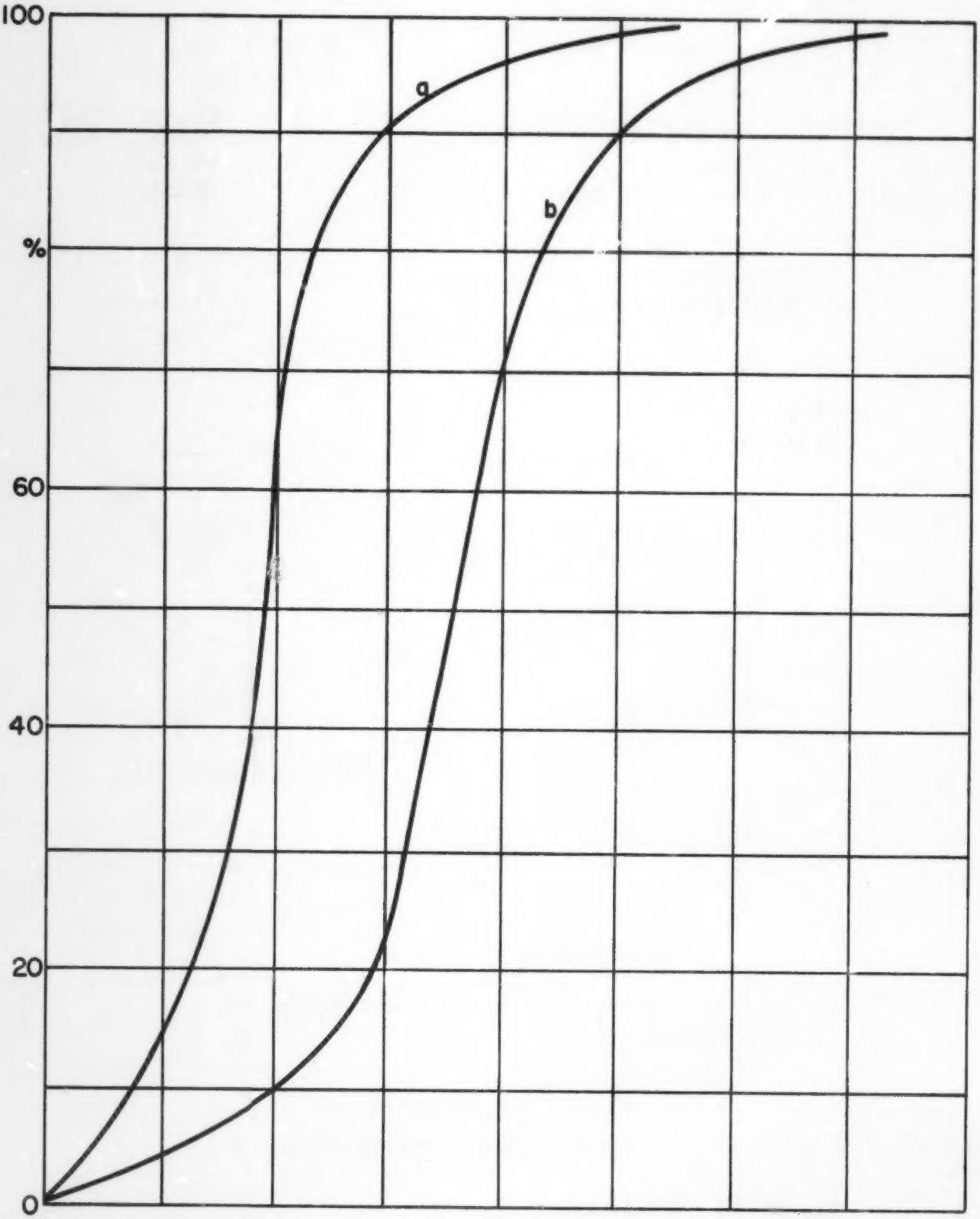


Fig. 4-12. Cyclone efficiency curves:
a) Small cyclone: 200 mm outer diameter.
b) Large cyclone: 1000 mm outer diameter.

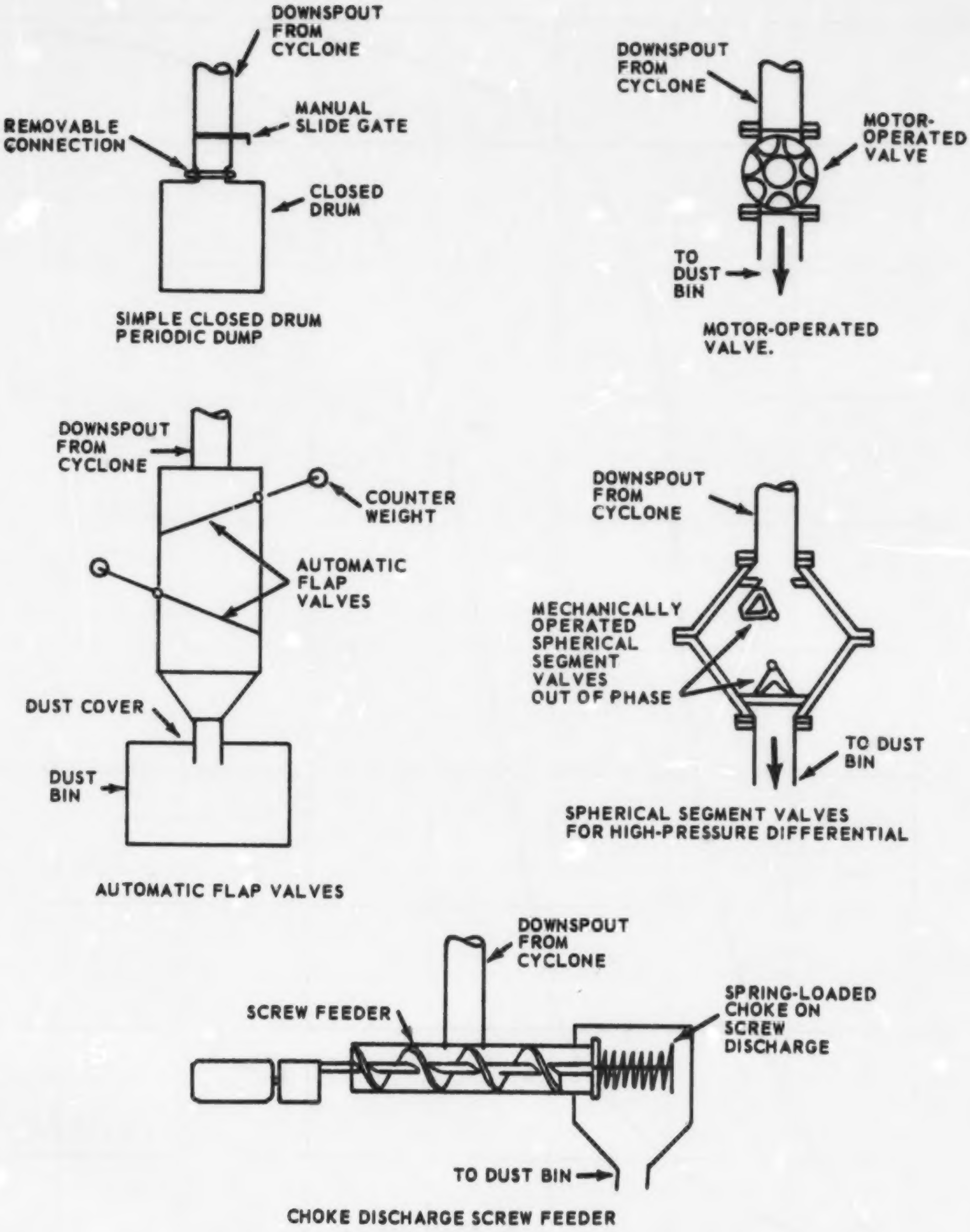

DOWNSPOUT FROM CYCLONE
MANUAL SLIDE GATE
REMOVABLE CONNECTION
CLOSED DRUM
SIMPLE CLOSED DRUM PERIODIC DUMP
DOWNSPOUT FROM CYCLONE
MOTOR-OPERATED VALVE
TO DUST BIN
MOTOR-OPERATED VALVE.
DOWNSPOUT FROM CYCLONE
COUNTER WEIGHT
AUTOMATIC FLAP VALVES
DUST COVER
DUST BIN
AUTOMATIC FLAP VALVES
DOWNSPOUT FROM CYCLONE
MECHANICALLY OPERATED SPHERICAL SEGMENT VALVES OUT OF PHASE
TO DUST BIN
SPHERICAL SEGMENT VALVES FOR HIGH-PRESSURE DIFFERENTIAL
DOWNSPOUT FROM CYCLONE
SCREW FEEDER
SPRING-LOADED CHOKE ON SCREW DISCHARGE
TO DUST BIN
CHOKE DISCHARGE SCREW FEEDER

Fig. 4-13. Various types of cyclone dust discharge.

the pressure drop may be as low as 124 N/m^2 of water. Pressure gains may even be realized with some units because of the pumping action of the motor-driven impeller.

A cyclone can be designed to handle practically any dust load that can be moved by gas flow. In general, efficiency increases with increasing dust load. Thus cyclones are frequently used as precleaners where dust loadings are too high for other final collectors. In addition, cyclones are usually used for dust loadings of more than 22.8 g/m^3, for coarse or easily flocculated dust loadings of less than 22.8 g/m^3, or for problems with high temperature and corrosion.

When cyclones are operated in parallel, gas distribution becomes critical and collection efficiency is usually lower than with a single unit. Series operation is sometimes used (1) if the dust is fragmented and deflocculated by bouncing within the cyclone, (2) if large particles must be removed to prevent clogging, (3) if abrasion is a problem, or (4) if the primary cyclone loses efficiency. In series operation, the primary cyclone is usually of large-diameter, low-pressure-drop design; smaller diameter cyclones with increased efficiency and pressure drop follow.

Abrasion increases exponentially with increasing gas velocity. Maximum abrasion occurs at an impingement angle of 0.35 to 0.53 rad and is approximately twice that occurring at 1.58 rad.[22] The effects of abrasion can be minimized by reducing gas velocity and by using special alloys, abrasion-resistant refractories, thicker walls, and rubber linings. A recent development that reduces abrasion is the three-phase dust arrester in which the cyclone wall is shielded from the abrasive by an auxiliary gas stream specially introduced for the purpose.[23]

4.2.3 Typical Applications

Cyclones are used in feed and grain mills, cotton gins, fertilizer plants, petroleum refineries, asphalt mixing plants, metallurgical operations, and in the manufacture of chemicals, plastics, and metals.[24] Performance and applications are listed in Tables 4-8 and 4-9.

4.3 WET COLLECTORS AND MIST ELIMINATORS

Wet collectors (scrubbers) use a liquid, usually water, to remove particulates by trapping them and washing them away.[31,32] Introduction of steam along with the liquid can sometimes promote particle separation.[33] Wet scrubbers have been thoroughly discussed in a recent systems study sponsored by the U.S. Environmental Protection Agency.[34] In practice, the principal mechanism by which particulates are brought into contact with liquid droplets[32] is inertial impaction. When an obstacle in the path of a particle-laden gas stream diverts the gas around the obstacle, large particles tend to flow in a straight path because of inertia and will be impacted and collected on the obstacle.

4.3.1 Description of Equipment

Wet collection equipment can be classified according to the source of energy used for liquid-vapor contacting. Some devices use energy from the liquid stream; others use the energy in the gaseous stream; still others introduce it through a mechanical device.

4.3.1.1 Devices Using Energy from Liquid Stream--Many systems that utilize liquid phase energy operate by using spray nozzles for liquid dispersion. Figure 4-14 illustrates spray nozzles available for liquid-vapor contacting. The contacting can be done in open spray chambers, in irrigated wet filters, in fixed-bed scrubbers, in fluidized bed scrubbers, or in venturi jet scrubbers.

Table 4-8. - REPRESENTATIVE PERFORMANCE OF CENTRIFUGAL COLLECTORS[24]

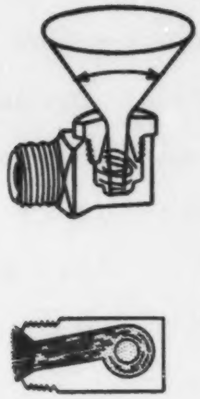
Collector type	Process and material	Airflow, m^3/s	Pressure drop, N/m^2	Efficiency, weight percent	Inlet load, g/m^3	Inlet mass median size, μm
Series cyclone	Fluid catalytic cracking--catalyst	18.8	High	99.98	6 400	37.0
Cyclone	Abrasive cleaning--talc	1.08	82.2	93.0	5.01	----
Cyclone	Drying--sand and gravel	5.65	474	86.9	86.6	8.2[a]
Cyclone	Grinding--aluminum	1.13	299	89.0	1.59	----
Cyclone	Planing mill--wood	1.46	922	97.0	0.23	----
Impeller	Grinding--iron scale	5.55	1 170	56.3	0.34	3.2[b]
Impeller	Rubber dusting--zinc stearate	1.55	2 240	88.0	1.36	0.7

[a] Outlet mass median size = 3.2 μm.

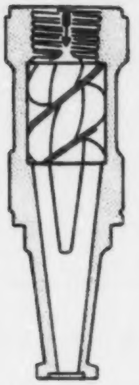
[b] Outlet mass median size = 2.5 μm.

Table 4-9. - APPLICATIONS OF CENTRIFUGAL COLLECTORS

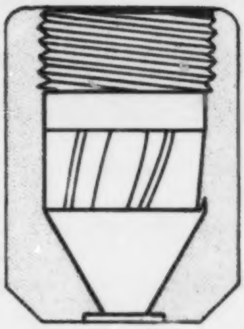
Operation or process	Air contaminant	Type of air-cleaning equipment	Collector efficiency, wt. percent	Ref.
Crushing, pulverizing, mixing, screening:				
Alfalfa feed mill	Alfalfa dust	Cyclone, settling chamber	85	25
Barley feed mill	Barley flour dust	Cyclone	85	25
Wheat air cleaner	Chaff	Cyclone	85	25
Drying, baking:				
Catalyst regenerator (petroleum)	Catalyst dust	Cyclone, ESP	95	25
Detergent powder spray drier	Detergent powder	Cyclone	85	25
Orange pulp feed drier	Pulp dust	Cyclone	85	25
Sand drying kiln	Silica dust	Cyclone	78	26
Sand and gravel drying	Silica dust	Inertial collector	50	27
Stone drying kiln	Silica dust	Cyclone	86	26
Mixing fluids:				
Asphalt mixing	Sand and gravel dust	Cyclone	50-86	26
Bituminous concrete mixing	Sand and stone dust	Cyclone, scrubber	95	28
Polishing, buffing, grinding, chipping:				
Grinding (aluminum)	Aluminum dust	Cyclone	89	29
Grinding (iron)	Iron scale and sand	Cyclone	56	27
Grinding (machine shop)	Dust	Impeller collector	91	30
Surface coating rubber dusting	Fluffy zinc stearate	Impeller collector	78-88	29
Surface treatment--physical:				
Abrasive cleaning	Talc dust	Cyclone	93	29
Abrasive stick trimming and shaping	Silicon carbide and alumina dust	2 parallel cyclones	51	26
Casting cleaning with metal shot, sandblasting and tumbling	Metallic and silica dust	Impeller collector	97-99+	30
Foundry tumbling	Dust	Impeller collector	99	30
Truing and shaping abrasive products	Silicon carbide and alumina dust	Cyclone	58	26
Woodworking, including plastics, rubber, paper board: mill planing	Wood dust and chips	Cyclone	97	29



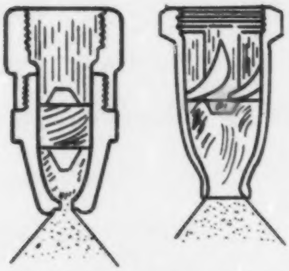
a. Hollow cone spray nozzle



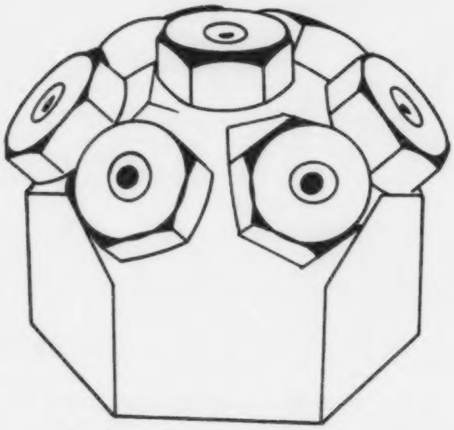
b. Hollow cone spray nozzle



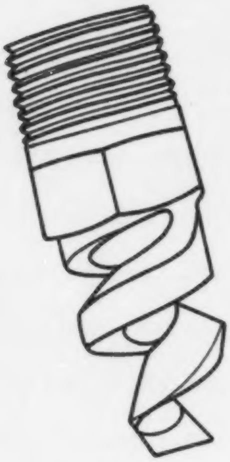
c. Hollow cone spray nozzle



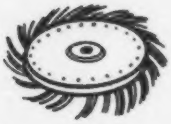
d. Solid cone spray nozzle



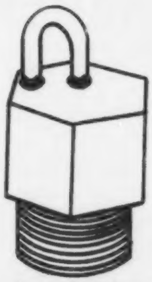
f. Cluster spray nozzle



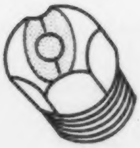
e. Solid cone spray nozzle



h. Spinning disk spray nozzle



g. Pin jet impingement spray nozzle



i. Monofan nozzle

Fig. 4-14. Spray nozzles commonly used in wet scrubbers.

An example of an open spray chamber is a spray system installed directly in a smokestack (Fig. 4-15). In the usual gravity spray tower (Fig. 4-16), liquid droplets from spray nozzles or atomizers fall through a rising gas stream containing dust particles. The gas passes through inlet conditioning sprays, through a base distributor plant, through one or more banks of spray nozzles, and through a mist eliminator section (usually necessary at gas velocities of over 1.8 m/s). The distributor may be a perforated plate with holes distributed uniformly on a support plate covered with from 0.152 to 0.305 m of packing. The scrubber illustrated in Fig. 4-17 employs swirling spray nozzles.

In irrigated wet filters (Fig. 4-18), an upper chamber contains wet filters and spray nozzles for cleaning the gas, and a lower chamber stores the scrubbing liquid. Recirculated liquid is sprayed on the upstream size of the bed onto the surface of two or more filter stages constructed in series. A dry bed of small diameter fibers, usually added as a final cleanup stage, removes spray mist.[35,36] The number of stages is determined by the characteristics of the gas stream and by the cleaning requirements. The chief mechanism of separation in irrigated wet filters is interception of particles by individual filter filaments; both particle removal and gas absorption can be accomplished, and the irrigation feature aids in removal of solids.

In fixed-bed scrubbers, the interfacial area is increased by adding packing. Typical packing materials are shown in Fig. 4-19.

Three fixed-bed designs are crossflow (Fig. 4-20a), countercurrent flow (Fig. 4-20b), and cocurrent flow.

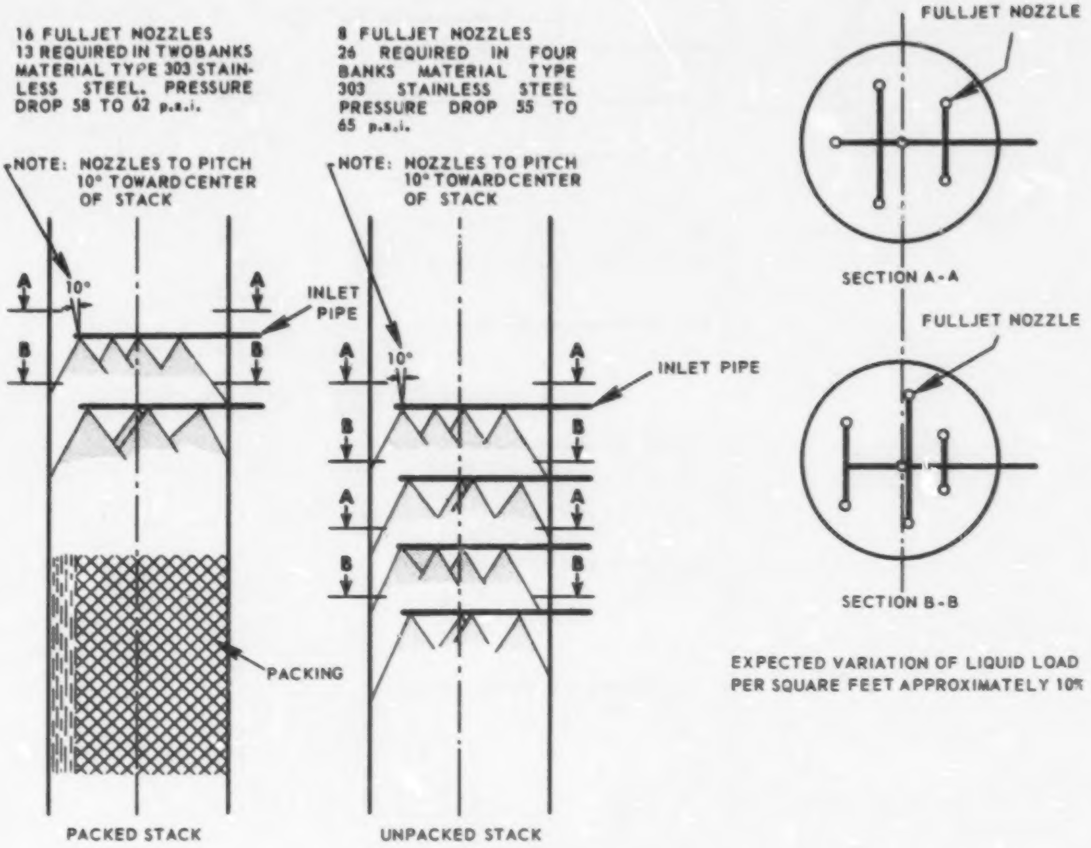

16 FULLJET NOZZLES
13 REQUIRED IN TWOBANKS MATERIAL TYPE 303 STAINLESS STEEL. PRESSURE DROP 58 TO 62 p.s.i.
NOTE: NOZZLES TO PITCH 10° TOWARD CENTER OF STACK
10°
A
B
INLET PIPE
PACKING
PACKED STACK
8 FULLJET NOZZLES
26 REQUIRED IN FOUR BANKS MATERIAL TYPE 303 STAINLESS STEEL PRESSURE DROP 55 TO 65 p.s.i.
NOTE: NOZZLES TO PITCH 10° TOWARD CENTER OF STACK
10°
A
B
INLET PIPE
UNPACKED STACK
FULLJET NOZZLE
SECTION A-A
FULLJET NOZZLE
SECTION B-B
EXPECTED VARIATION OF LIQUID LOAD PER SQUARE FEET APPROXIMATELY 10%

Fig. 4-15. Arrangement of nozzles in smokestack spray system.

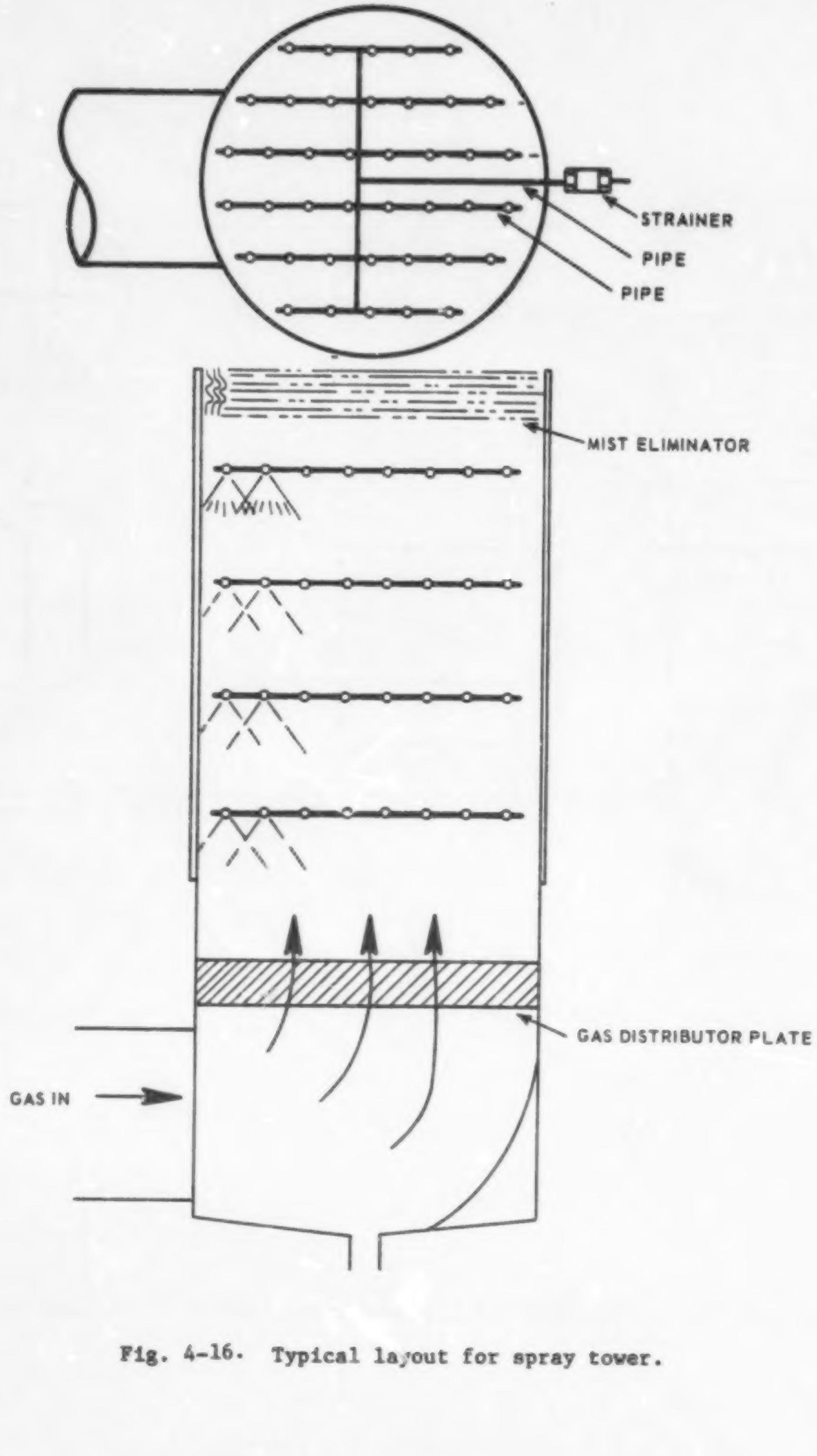

STRAINER
PIPE
PIPE
MIST ELIMINATOR
GAS DISTRIBUTOR PLATE
GAS IN

Fig. 4-16. Typical layout for spray tower.

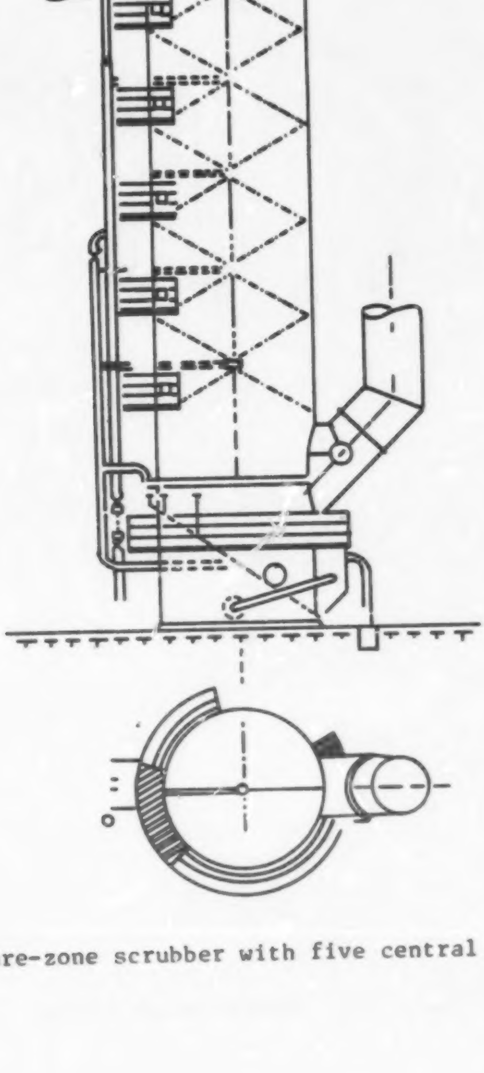


Fig. 4-17. Pressure-zone scrubber with five central swirl nozzles.

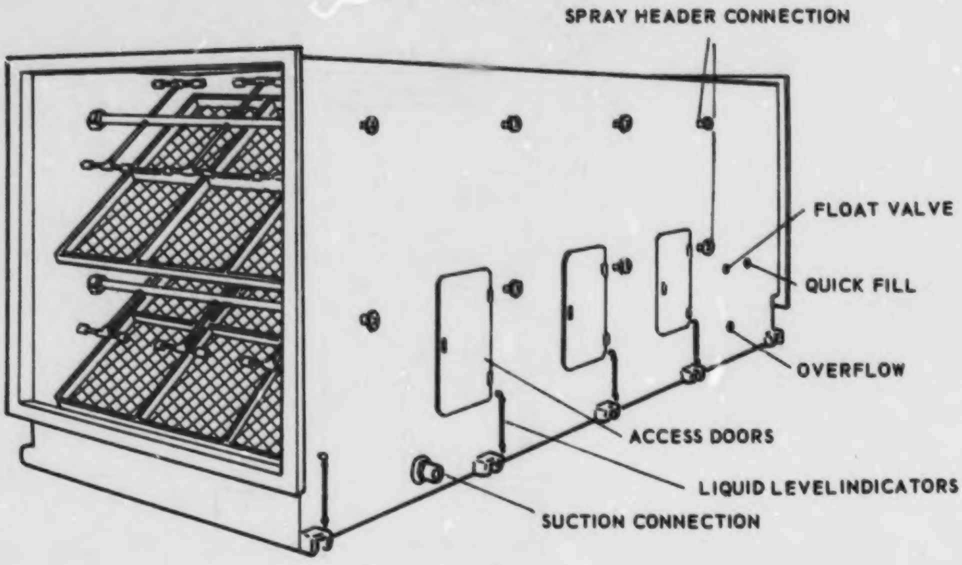
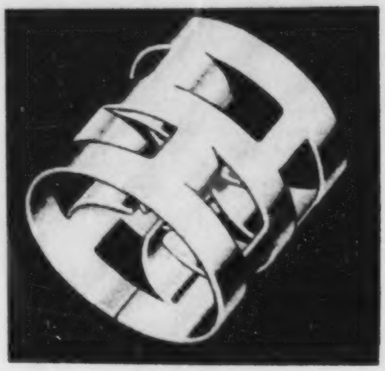
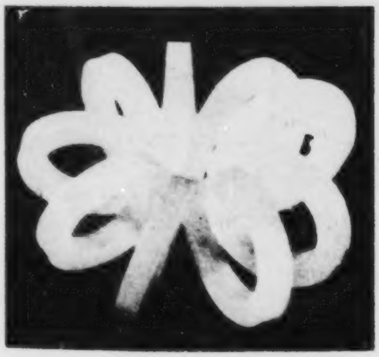

SPRAY HEADER CONNECTION
FLOAT VALVE
QUICK FILL
OVERFLOW
ACCESS DOORS
LIQUID LEVEL INDICATORS
SUCTION CONNECTION

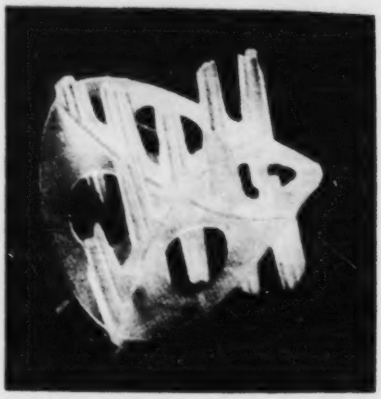
Fig. 18. Wetted plate filter.



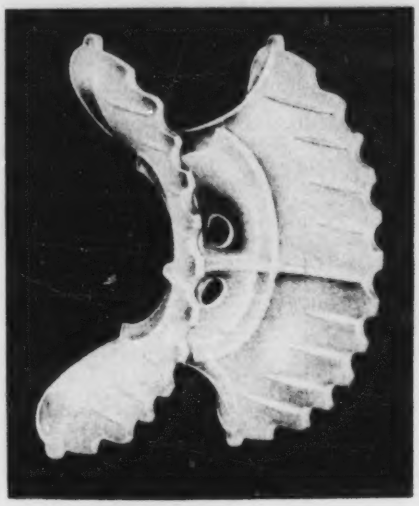
PALL RING



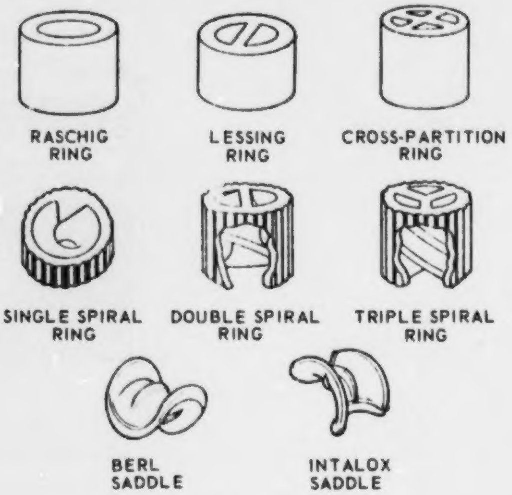
TELLERETTE



MASPAC



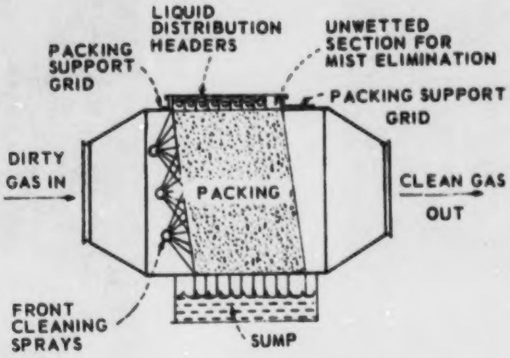
PLASTIC INTALOX SADDLE



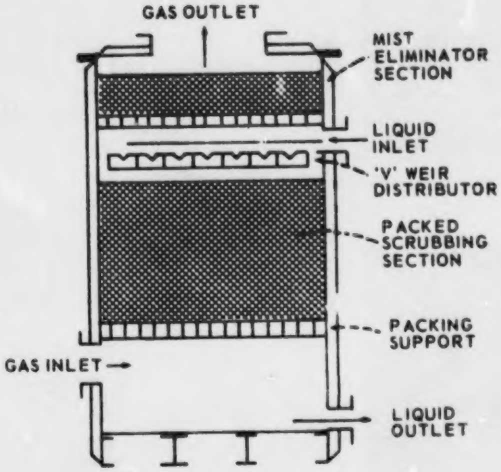
RASCHIG RING
LESSING RING
CROSS-PARTITION RING
SINGLE SPIRAL RING
DOUBLE SPIRAL RING
TRIPLE SPIRAL RING
BERL SADDLE
INTALOX SADDLE

CERAMIC PACKINGS

Fig. 4-19. Wet scrubber packings.


LIQUID DISTRIBUTION HEADERS
PACKING SUPPORT GRID
UNWETTED SECTION FOR MIST ELIMINATION
PACKING SUPPORT GRID
DIRTY GAS IN
PACKING
CLEAN GAS OUT
FRONT CLEANING SPRAYS
SUMP

a. CROSS-FLOW SCRUBBER


GAS OUTLET
MIST ELIMINATOR SECTION
LIQUID INLET
'V' WEIR DISTRIBUTOR
PACKED SCRUBBING SECTION
PACKING SUPPORT
GAS INLET
LIQUID OUTLET

b. COUNTERCURRENT-FLOW SCRUBBER

Fig. 4-20. Packed-bed scrubbers.

In the crossflow fixed-bed scrubber (Fig. 4-20a), the gas stream moves horizontally, and the irrigating liquid flows downward by gravity through the packing. The leading face of the packed bed is usually slanted from 0.12 to 0.18 rad (depending on gas velocity) toward the oncoming gas stream to ensure complete wetting and washing of the face by the irrigation liquid. Inlet sprays condition the inlet gas and scour the face of the bed. The first few centimeters of the bed may be irrigated heavily to prevent buildup of solids. The back of the bed is usually a dry demisting section.[37]

In countercurrent flow (Fig. 4-20b), the most common design used in fixed beds, gas is forced upward through the packing against the gravity flow of the liquid. This type of scrubber works best at a gas velocity and pressure drop that cause the buildup of water in and on top of the bed.[38] A higher pressure drop usually causes excessive liquid entrainment and reduces efficiency.

In cocurrent, or parallel, flow the gas stream and the irrigation liquid pass through the bed in the same direction; the liquid keeps the packed bed from clogging, and both the gas and the liquid wash the solids through the bed. The major advantage to this configuration is the small liquid requirement.

In fluidized-bed scrubbers, the packing is fluidized, or maintained in motion, by the fluids being processed. Fluidized-bed scrubbers are operated, on occasion, just above the point of incipient fluidization; in this mode of operation, the movement of the packing is minimal. One such device (Fig. 4-21) has been termed the "flooded-bed" scrubber. Dust- and fume-laden air passing through a 6-inch thick bed packed with glass marbles forms bubbles which cause a constant, gently rubbing

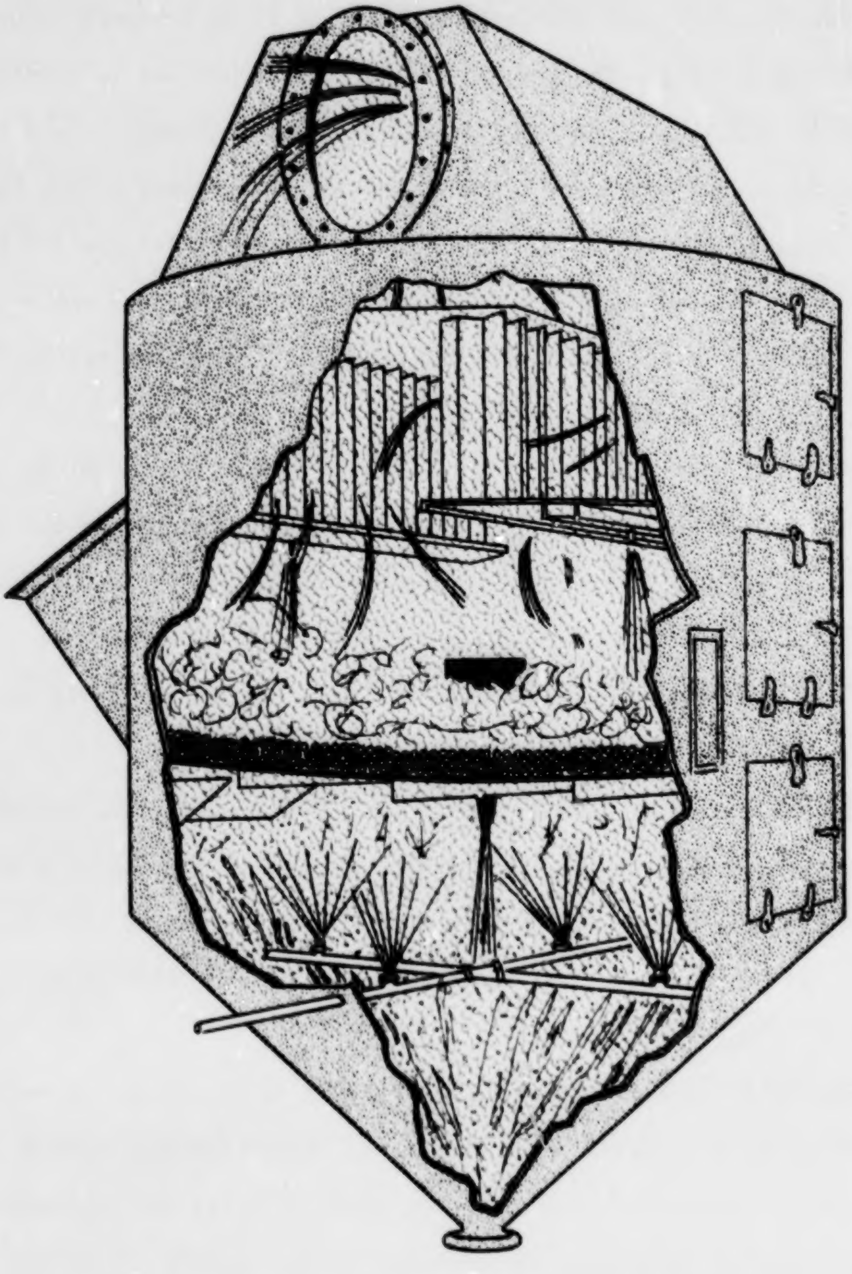


Fig. 4-21. Flooded-bed scrubber.

motion that cleans the marbles. Entrained moisture is removed by impaction or inertial separation in a mist eliminator section.

More often, the fluidization is more violent. In a typical design (Fig. 4-22), the packing is low density polyethylene or polypropylene spheres, about 0.038 m in diameter, that are continuously in motion between the upper and lower retaining grids.[39] The scrubbing liquid is sprayed downward over the balls through a countercurrent flow of dirty gas; thus, the gas and liquid are brought into contact on the surface of the wetted spheres and in the spaces between them, and the spheres are cleaned by constant motion so the bed is not easily plugged.

In the venturi jet scrubber, the liquid is supplied as a high-velocity jet along the axis of a venturi throat. The liquid pumps, scrubs, and/or absorbs the entrained gas. The mechanical efficiency of the jet stream in pumping the gas may be as high as 16 to 17 percent. Increased collection efficiency requires increased energy expenditure.[40,41]

4.3.1.2 Devices Using Energy from Gaseous Stream--Among the most common devices that use gaseous energy in the mixing process are two types of wet cyclones--or centrifugal spray scrubbers--the self-induced spray scrubber, the venturi scrubber, the flooded disc scrubber, and the vertical venturi scrubber.

In the first type of wet cyclone, the spinning motion is imparted to the gas stream by a tangential entry (Fig. 4-23a). The wetted walls prevent reentrainment of separated material. Figure 4-23b shows a tangential base gas inlet: the liquid is sprayed outward from nozzles in a central pipe, an unsprayed section above the nozzles is provided to

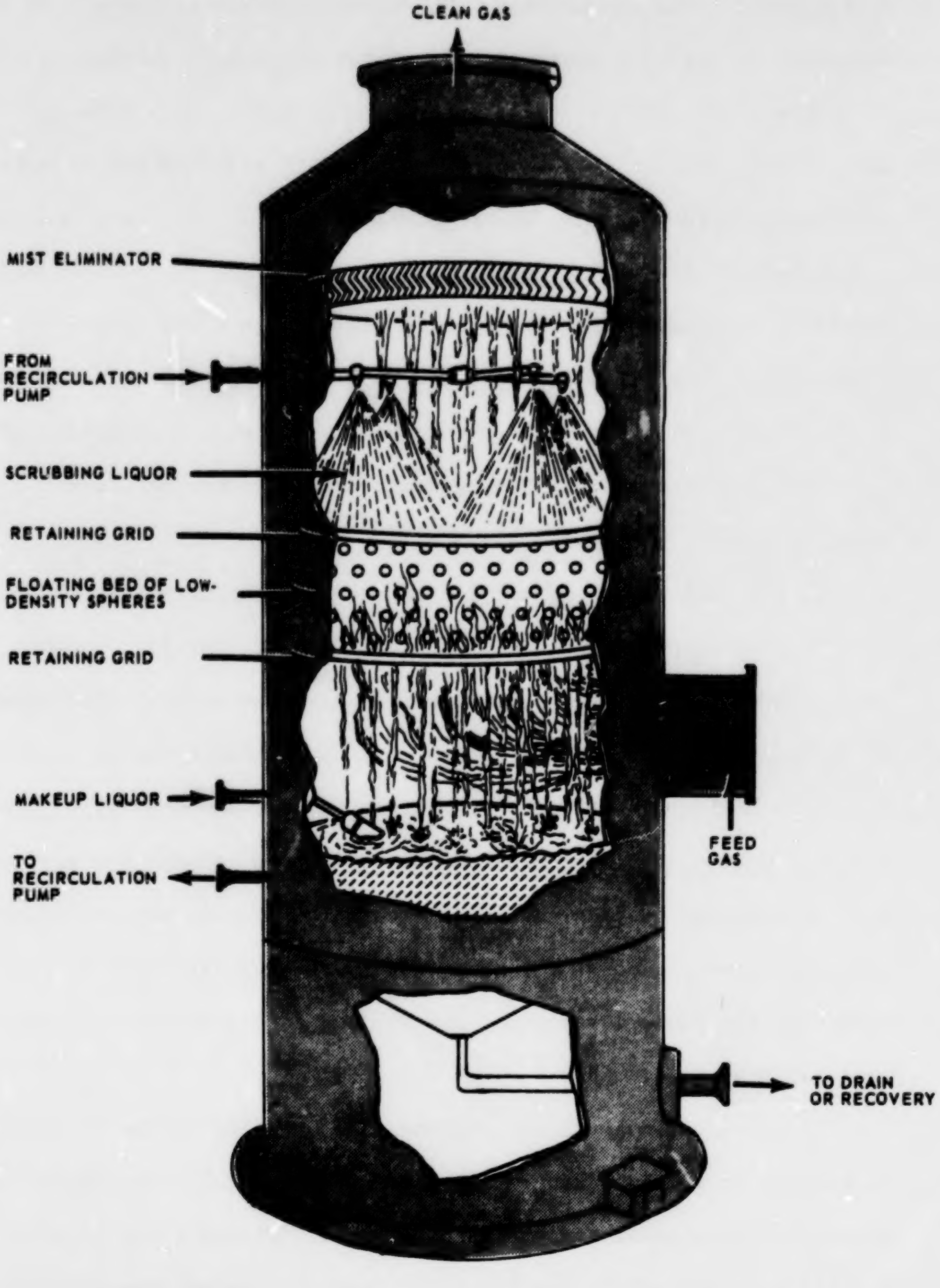
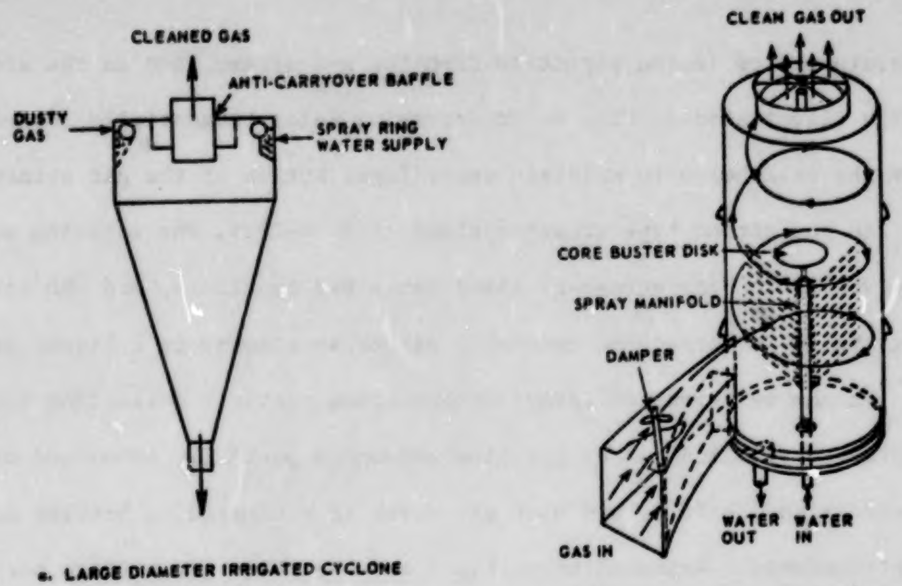
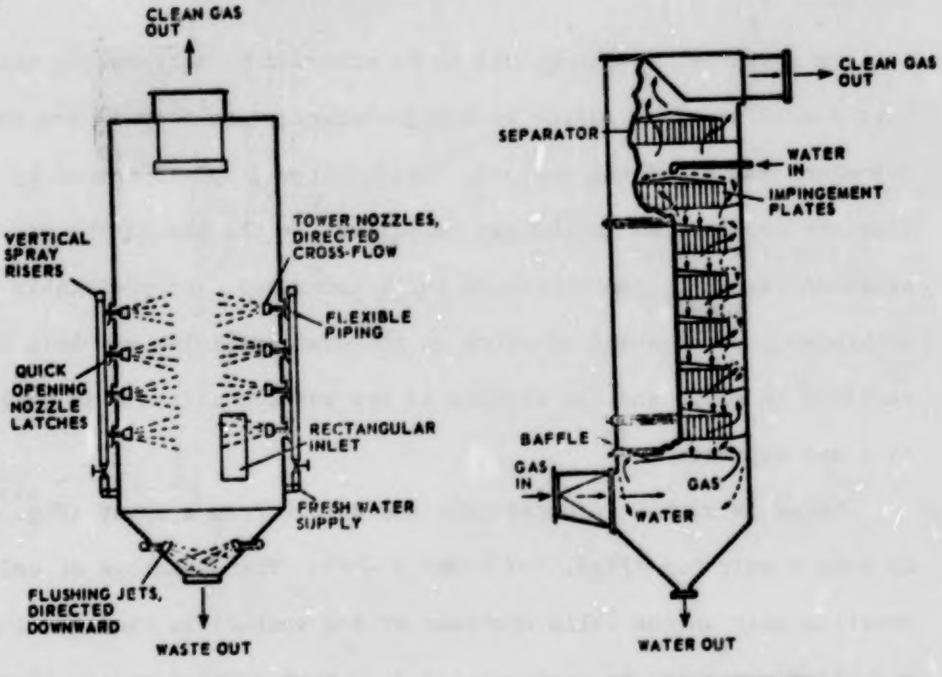

CLEAN GAS
MIST ELIMINATOR
FROM RECIRCULATION PUMP
SCRUBBING LIQUOR
RETAINING GRID
FLOATING BED OF LOW-DENSITY SPHERES
RETAINING GRID
MAKEUP LIQUOR
FEED GAS
TO RECIRCULATION PUMP
TO DRAIN OR RECOVERY

Fig. 4-22. Floating-ball (fluid-bed) packed scrubber.


CLEANED GAS
ANTI-CARRYOVER BAFFLE
DUSTY GAS
SPRAY RING WATER SUPPLY
CLEAN GAS OUT
CORE BUSTER DISK
SPRAY MANIFOLD
DAMPER
WATER OUT
WATER IN
GAS IN

a. LARGE DIAMETER IRRIGATED CYCLONE

b. PEASE ANTHONY CYCLONIC SCRUBBER
(Courtesy of Chemical Construction Corporation)


CLEAN GAS OUT
VERTICAL SPRAY RISERS
TOWER NOZZLES, DIRECTED CROSS-FLOW
FLEXIBLE PIPING
QUICK OPENING NOZZLE LATCHES
RECTANGULAR INLET
FRESH WATER SUPPLY
FLUSHING JETS, DIRECTED DOWNWARD
WASTE OUT
CLEAN GAS OUT
SEPARATOR
WATER IN
IMPINGEMENT PLATES
BAFFLE
GAS IN
GAS
WATER
WATER OUT

c. CYCLONIC SPRAY SCRUBBER.
(Courtesy of Buffalo Forge Company)

d. MULTI-WASH SCRUBBER.
(Courtesy of Claude B. Schneible Company)

Fig. 4-23. Centrifugal spray scrubbers.

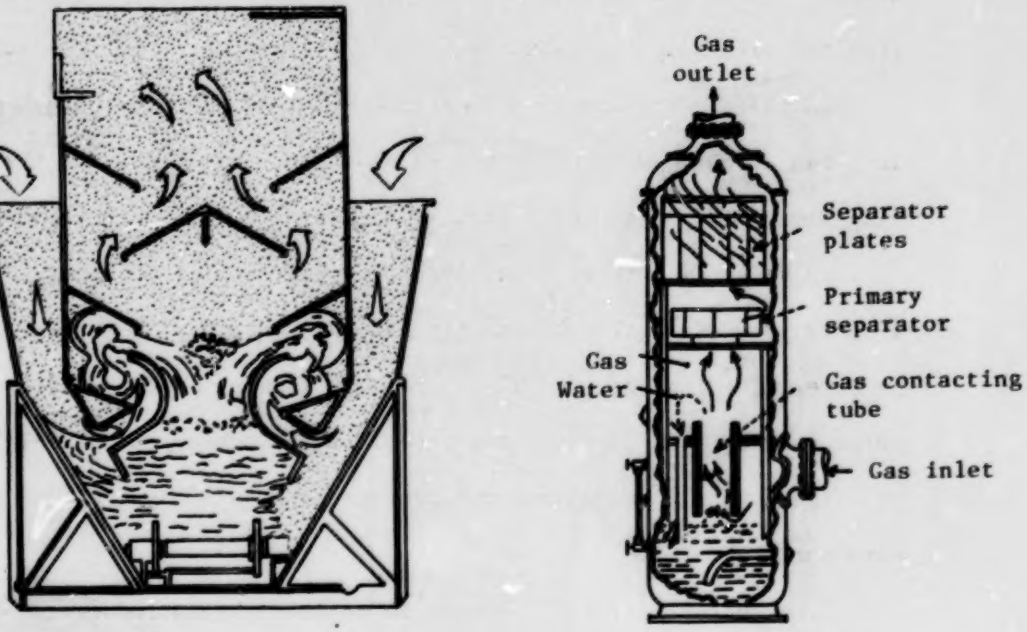
separate the collected particles from the gas stream, and in the alternate design illustrated in Fig. 4-23c, spraying water tangentially inward from the wall helps to maintain centrifugal motion of the gas stream.

In the second type of wet cyclone (Fig. 4-23d), the rotating motion is given to the gas stream by fixed vanes and impellers, and the scrubbing liquid is introduced centrally either as a spray or a liquid stream.[42]

In the self-induced spray scrubber, the particle collection zone is a spray curtain induced by gas flow through a partially submerged orifice or streamlined baffle, and mist carryover is minimized by baffles or swirl chambers. Representative types are the submerged orifice scrubber (Fig. 4-24a), the Blaw Knox scrubber (Fig. 4-24b), and the Doyle scrubber (Fig. 4-24c).

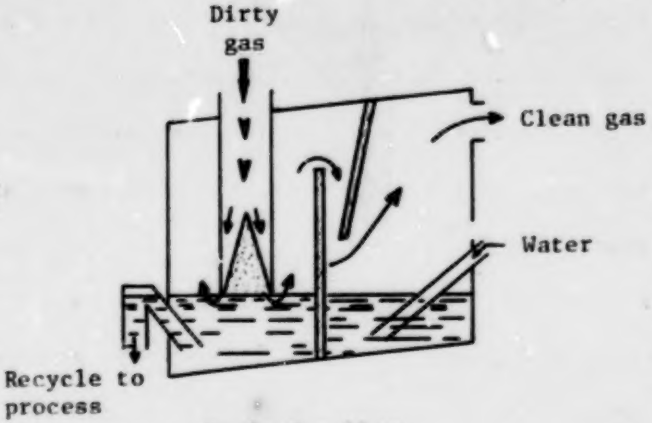
In a venturi scrubber, mixing is achieved by introducing the scrubbing liquid at right angles to a high-velocity gas flow in the throat (vena contracta) of the venturi. Small water droplets formed by the gas flow are accelerated to the gas velocity. If the gas in the reduced-pressure region in the throat is fully saturated (or preferably supersaturated), condensation of water on the dust particles may help the particle to grow, and the wetness of its surface will aid in agglomeration and separation.[43]

Water is either injected into the throat from a spray (Fig. 4-25a) or from a weir box (Figs. 4-25b and 4-25c). The advantage of using an overflow weir on the walls upstream of the venturi is that the injected scrubbing water can be recirculated to a much greater extent than with systems using small jets. Recent interests in finding water injection methods that reduce nozzle wear and pump requirements and methods of maintaining pressure drop and scrubbing efficiency with varying gas flow


Gas
outlet
Separator
plates
Primary
separator
Gas
Water
Gas contacting
tube
Gas inlet

a. Schmieg swirl-orifice dust collector

b. Liquid vortex contactor


Dirty
gas
Clean gas
Water
Recycle to
process

c. **Doyle** Scrubber

Fig. 4-24. Self-induced spray scrubbers.

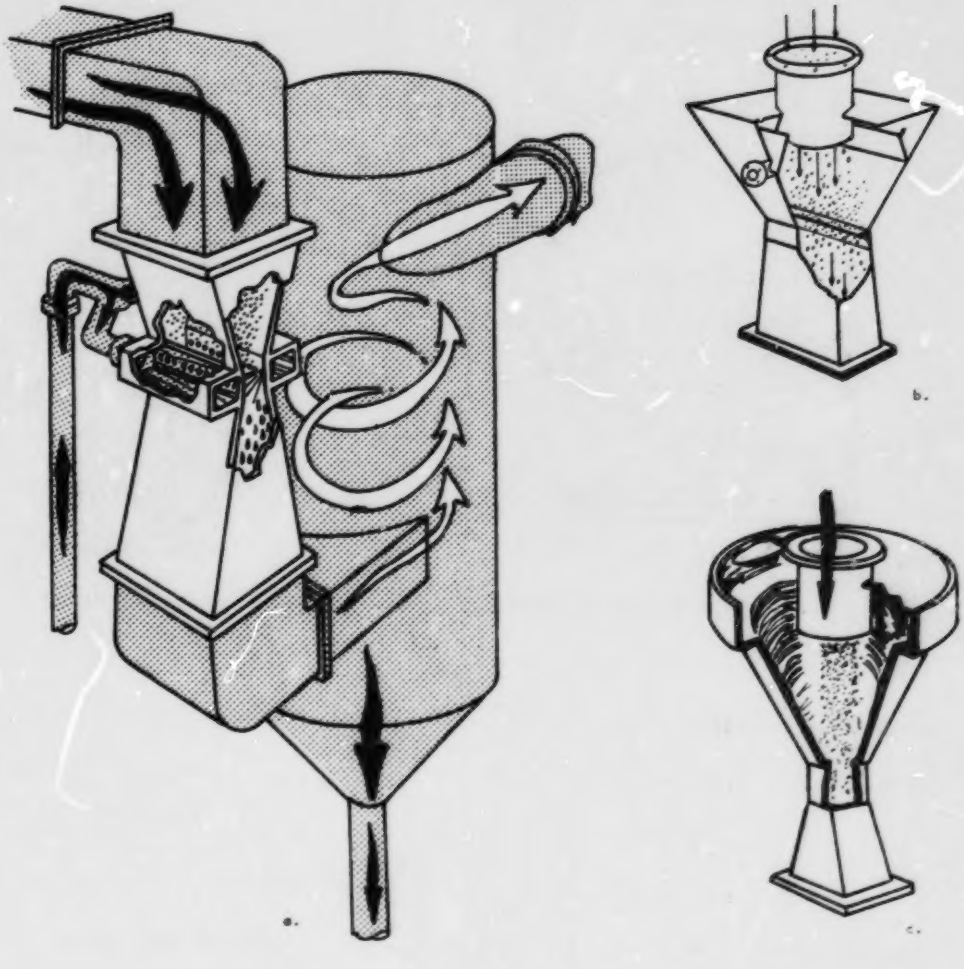


Fig. 4-25. Venturi scrubber may feed liquid through jets (a), over a weir (b), or swirl it on a shelf (c).

rates have resulted in the development of variable venturi throats.

Improved separation efficiencies have been noted when the liquid is superheated, possibly by heat exchange against flue gas,[44] prior to injection into the venturi throat and allowed to flash into the gas.[45] The flashing action seems to generate small droplets which are efficient dust collectors. Cloud-type atomization also produces more efficient particle separation than does droplet-type atomization.[46] Sonic energy is also effective as an atomizing agent.[47]

The flooded disk (variable throat orifice scrubber, Fig. 4-26) is a relatively new development.[48] Scrubbing liquid is fed to the center of the orifice plate which distributes the liquid across the orifice throat. The pressure drop and the efficiency, which are comparable to other venturi scrubbers, can be adjusted by changing the position of the disk.

The vertical venturi differs from the conventional venturi scrubber--the gas flow is directed upward to produce a turbulent mixing of the gas with the suspended liquid in the diffuser section (Fig. 4-27). Liquid recirculates internally by eddy mixing in the diffuser and externally by return of the scrubbing liquid, after partial separation, to the throat. The carryover slurry, when separated by the centrifugal action of the gas stream caused by the stationary impeller, returns by gravity to the solids concentrator. The advantages of this design are high solids content of slurry, low water usage, elimination of a recirculation pump, relatively low pressure drop, and low operating costs.[39]

The ring gap scrubber (Fig. 4-28) is a relatively new development which employs a cone-shaped body within a cone-shaped shell. The ring gap is the distance between the body and the shell. By displacing the body in an axial direction, the cross-sectional area of the gas stream

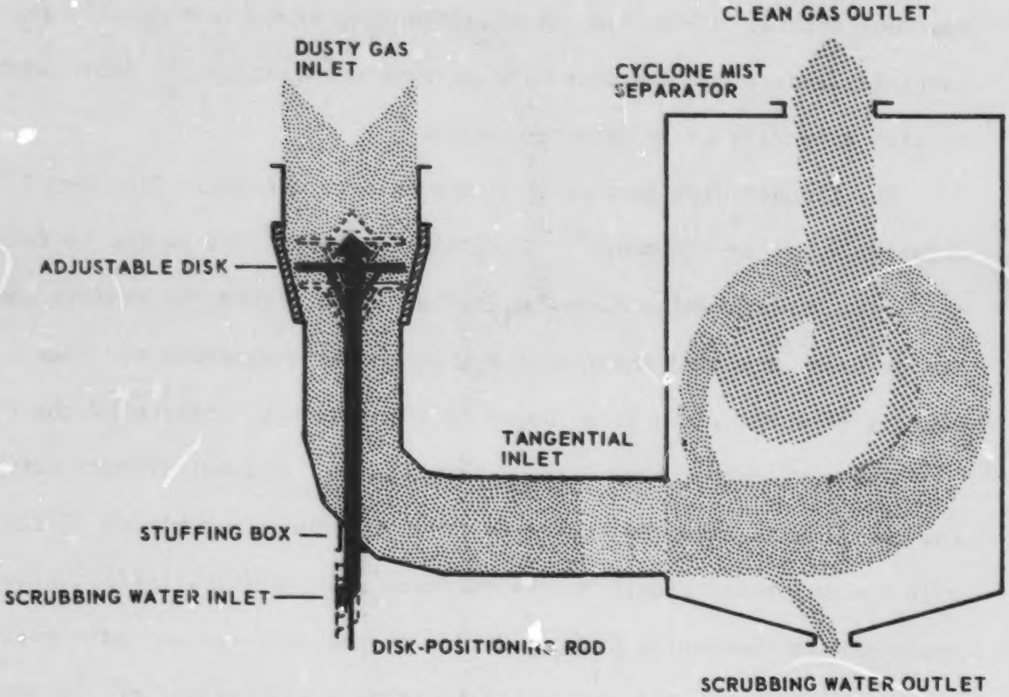

CLEAN GAS OUTLET
DUSTY GAS INLET
CYCLONE MIST SEPARATOR
ADJUSTABLE DISK
TANGENTIAL INLET
STUFFING BOX
SCRUBBING WATER INLET
DISK-POSITIONING ROD
SCRUBBING WATER OUTLET

Fig. 4-26. Flooded disk (variable throat orifice) scrubber.

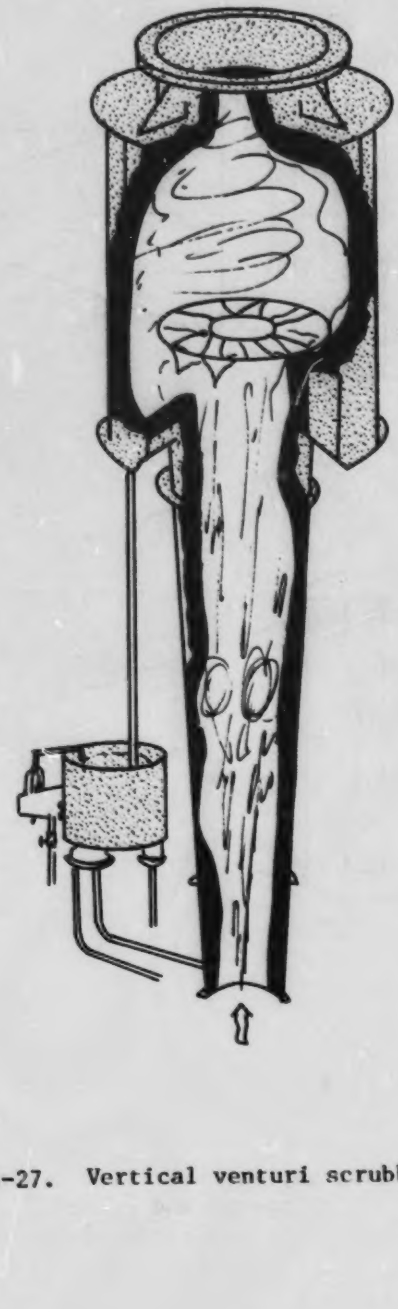


Fig. 4-27. Vertical venturi scrubber.

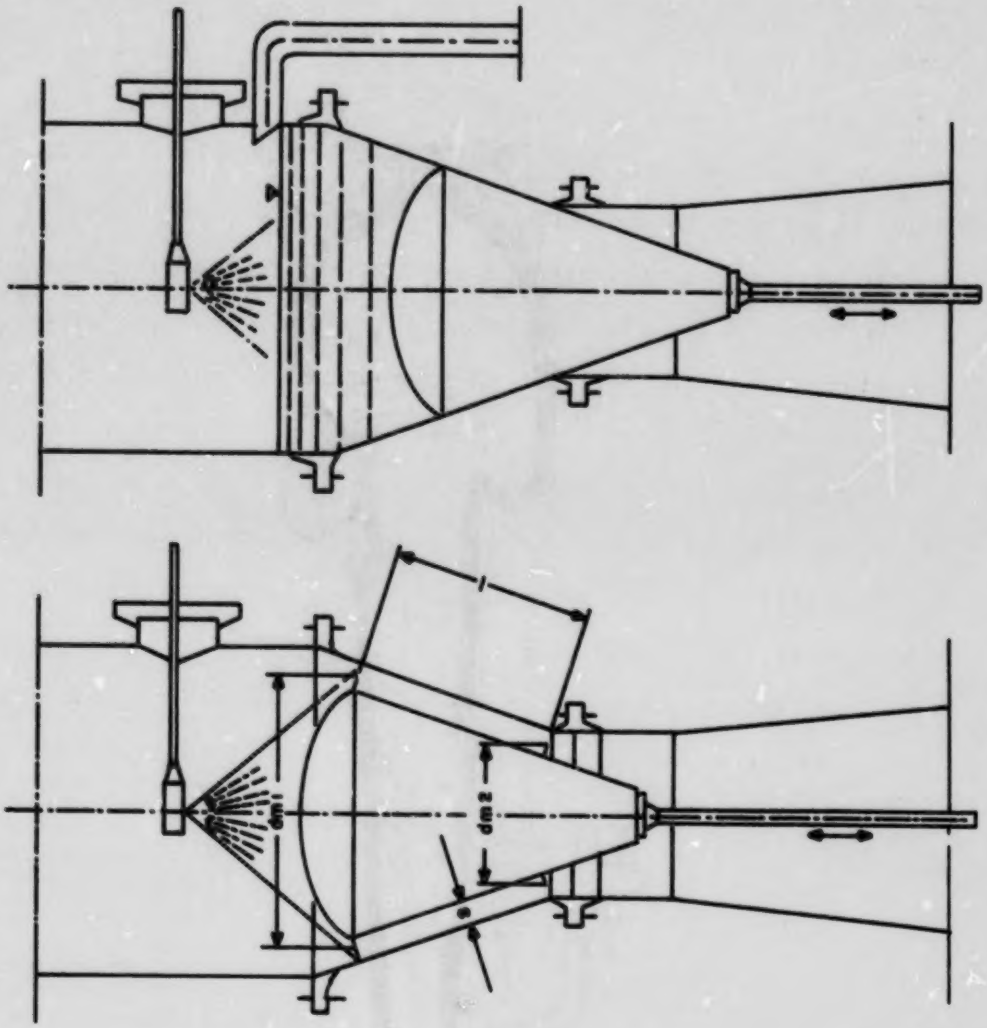


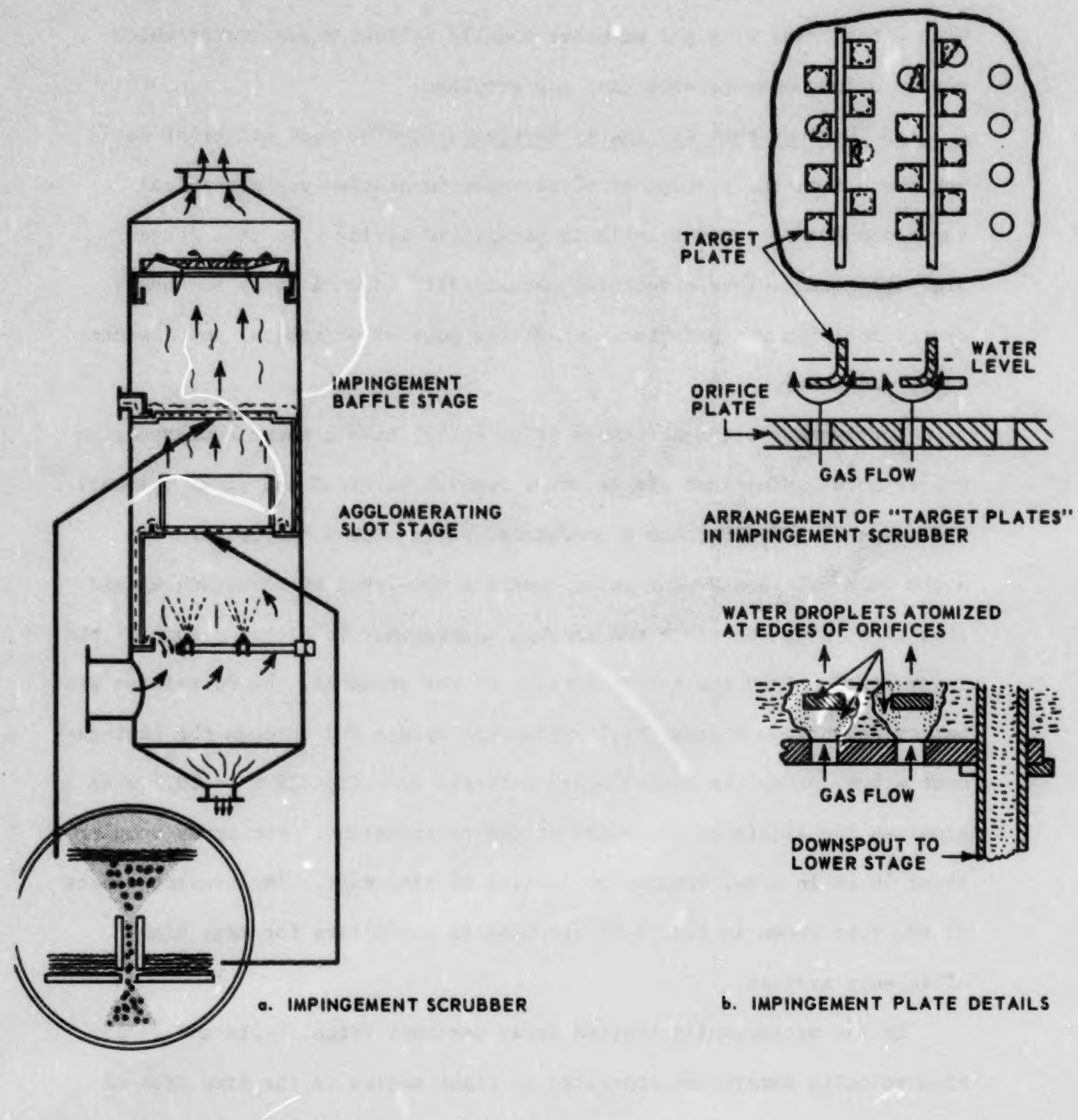
Fig. 4-28. Ring gap scrubber with central swirl nozzle opened and closed.

and, therefore, the gas velocity can be varied. Water is injected through a swirl nozzle. Ring gap elements can be used parallel to each other. The ring gap scrubber usually follows a precleaner which may be a low pressure drop ring gap scrubber.

4.3.1.3 Devices that Add Energy Mechanically--The most efficient wet scrubbers from the standpoint of particle separation use mechanical appurtenances to achieve intimate gas-liquid mixing. In this category are impingement plate scrubbers, mechanically induced spray scrubbers, centrifugal fan wet scrubbers, axial-fan-powered scrubbers, and disintegrator scrubbers.

Impingement plate scrubbers (Fig. 4-29a) have a tower equipped with one or more impingement stages, mist removal baffles, and spray chambers.[49] The stage (Fig. 4-29b) has a perforated plate with a baffle directly above each hole and a weir which controls the level of scrubbing liquid that flows over the plate and through a downcomer to either a sump or the lower stage. From the bottom section of the scrubber, the dust-laden gas passes up through a group of low-pressure sprays and through the impingement stage, where the high gas and particle velocity (22.9 to 30.5 m/s) atomizes the liquid at the edges of the perforations. The spray droplets, about 10 μm in size, enhance collection of fine dust. Impingement plates of the type shown in Fig. 4-30 are used as prefilters for many high-efficiency systems.

In the mechanically induced spray scrubber (Figs. 4-31a and 4-31b), high velocity sprays are generated at right angles to the direction of gas flow by a partially submerged rotor, and scrubbing is achieved by impaction because of both high radial droplet velocity and vertical gas velocity. Liquid atomization occurs at the rotor and at the outer wall.[50] Advantages are relatively low liquid requirement, small space requirement,


IMPINGEMENT BAFFLE STAGE
AGGLOMERATING SLOT STAGE
TARGET PLATE
WATER LEVEL
ORIFICE PLATE
GAS FLOW
ARRANGEMENT OF "TARGET PLATES" IN IMPINGEMENT SCRUBBER
WATER DROPLETS ATOMIZED AT EDGES OF ORIFICES
GAS FLOW
DOWNSPOUT TO LOWER STAGE

a. IMPINGEMENT SCRUBBER

b. IMPINGEMENT PLATE DETAILS

Fig. 4-29. Impingement plate scrubber.

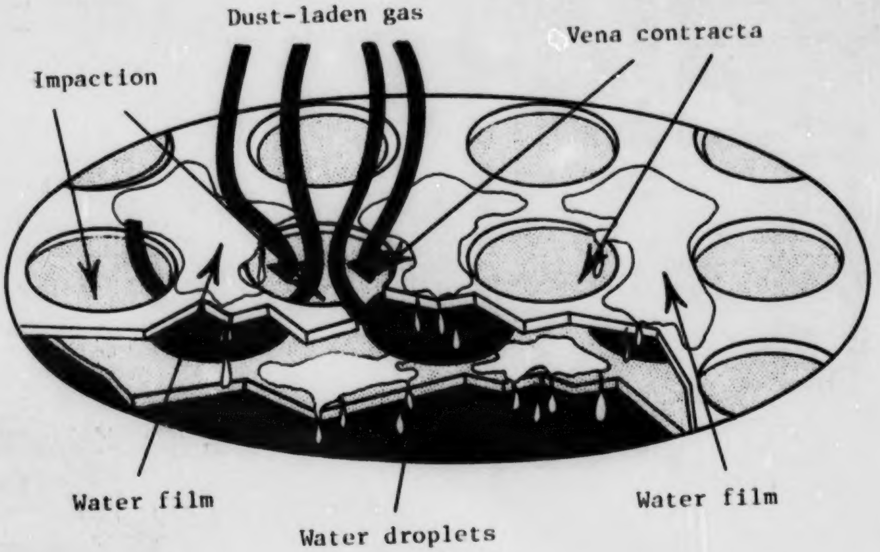
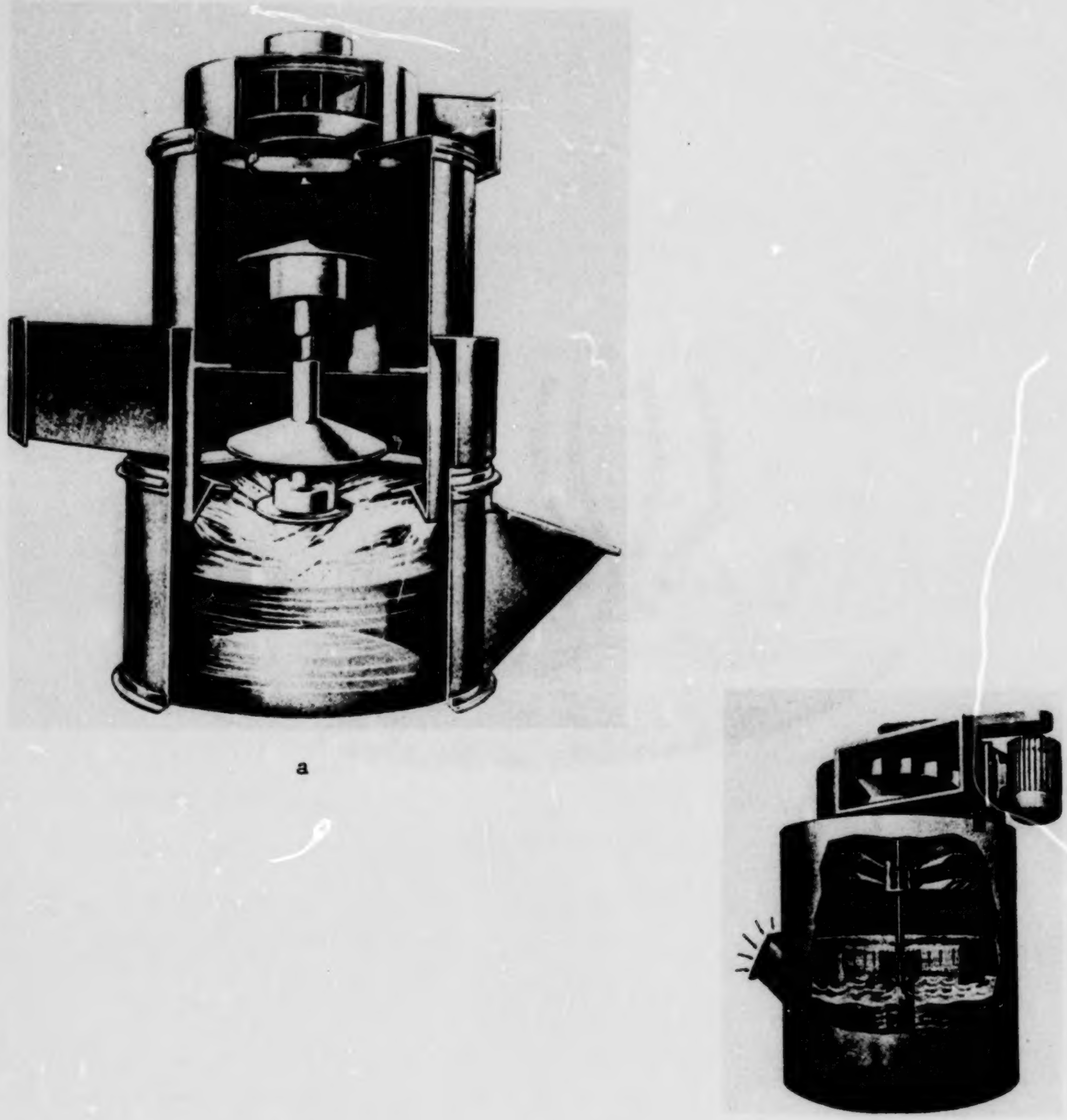

Dust-laden gas
Vena contracta
Impaction
Water film
Water droplets
Water film

Fig. 4-30. Impingement plate filter.



a

b

Fig. 4-31. Mechanically induced spray scrubbers.

high scrubbing efficiency, and high dust-load capacity. The rotor, however, is susceptible to abrasion by large particles and abrasive dusts. High-energy scrubbing applications may require mist eliminators.

The centrifugal fan wet scrubber (Fig. 4-32) is essentially a multiple blade, centrifugal blower. The advantages are low space requirement, moderate power requirement, low water consumption, and a relatively high scrubbing efficiency.

In the axial-fan-power gas scrubber (Fig. 4-33), a water spray and baffle screen wet the particles, and centrifugal fan action eliminates the wetted particles through concentric louvers. Advantages of the in-line wet scrubber are low space requirement and low installation cost.

A disintegrator scrubber (Fig. 4-34) has a barred rotor within a barred stator. Water is injected axially through the rotor shaft and separated into fine droplets by the relatively high velocity of rotor and stator bars; dust particles are impacted by the high velocity droplets. Advantages of this scrubber are high collection efficiency for submicron particles and low requirements for space. The main disadvantage is its large power requirement.

4.3.1.4 Mist Eliminators--Wet fiber mist eliminators are either low velocity (0.03 to 0.15 m/s, Fig. 4-35) or high velocity (2.04 to 2.55 m/s, Fig. 4-36). The low-velocity design has a packed bed of fibers between two concentric screens. Mist particles collect on the surface of the fibers, coalesce to form a liquid film that wets the fibers, and move horizontally downward by the force of gravity and the drag of the gases; the liquid flows down the inner scrren to the bottom of the element and through a liquid seal to a collection reservoir.

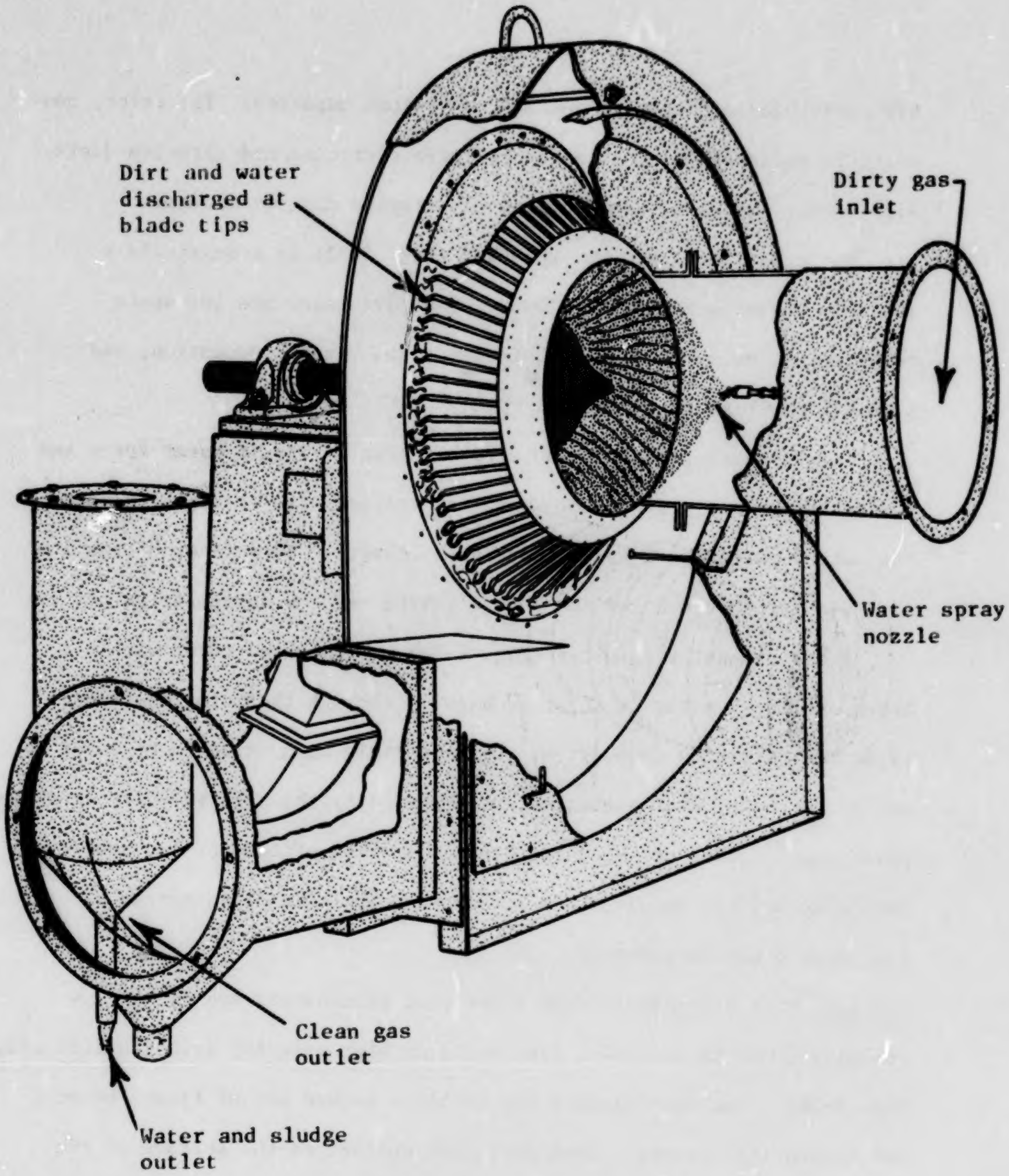

Dirt and water discharged at blade tips
Dirty gas inlet
Water spray nozzle
Clean gas outlet
Water and sludge outlet

Fig. 4-32. Centrifugal fan wet scrubber.

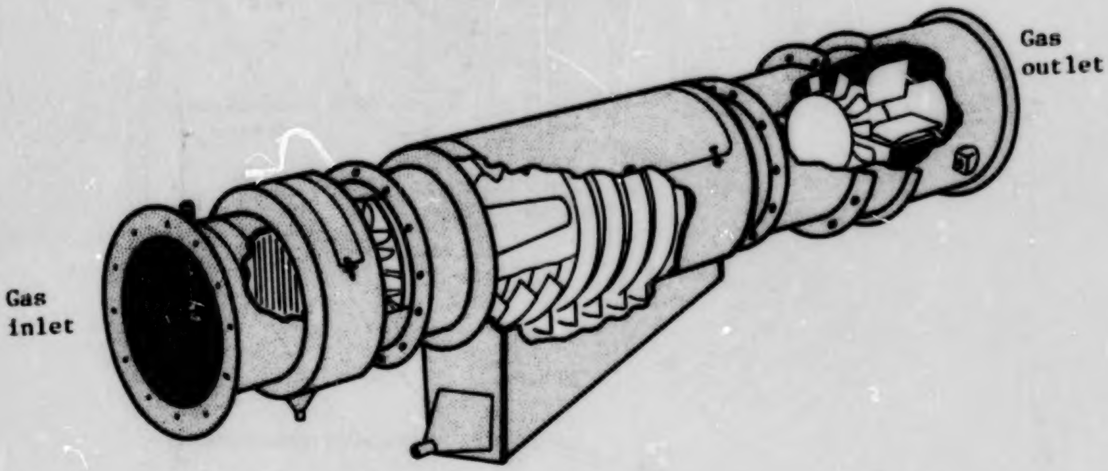

Gas
outlet
Gas
inlet

Fig. 4-33. Inline wet scrubber.

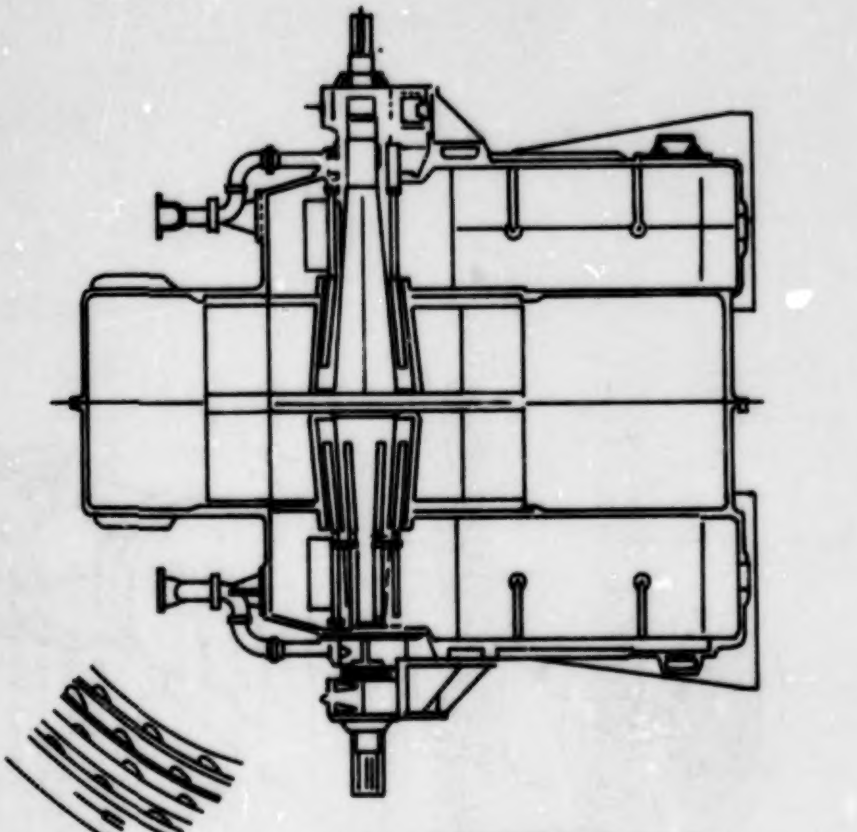
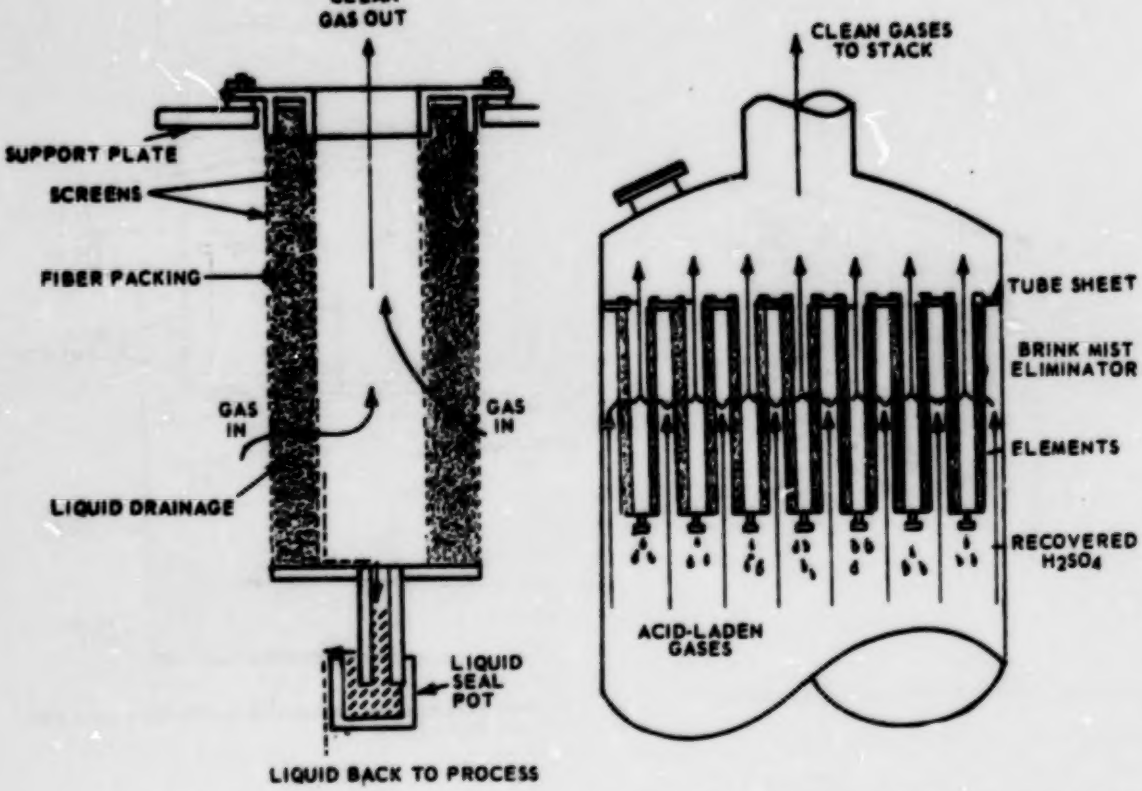


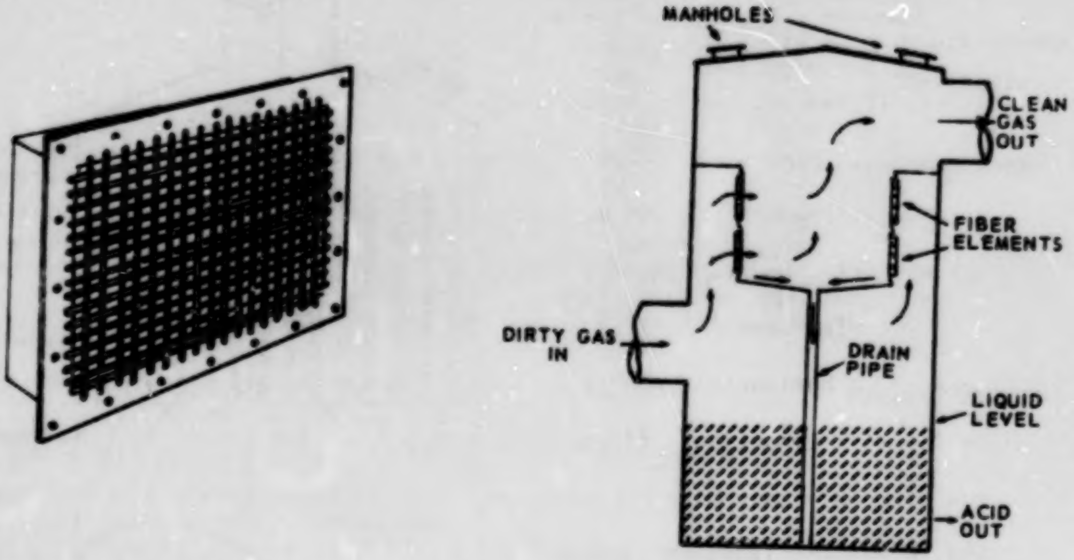
Fig. 4-34. Radial disintegrator scrubber.


CLEAN GAS OUT
SUPPORT PLATE
SCREENS
FIBER PACKING
GAS IN
GAS IN
LIQUID DRAINAGE
LIQUID SEAL POT
LIQUID BACK TO PROCESS
CLEAN GASES TO STACK
TUBE SHEET
BRINK MIST ELIMINATOR
ELEMENTS
RECOVERED H_2SO_4
ACID-LADEN GASES

a. LOW-VELOCITY FILTERING ELEMENT

b. MULTIPLE MOUNTING OF LOW-VELOCITY FILTERING ELEMENTS

Fig. 4-35. Low-velocity filtering elements.


MANHOLES
CLEAN GAS OUT
FIBER ELEMENTS
DIRTY GAS IN
DRAIN PIPE
LIQUID LEVEL
ACID OUT

a. HIGH-VELOCITY FILTERING ELEMENT

b. MULTIPLE MOUNTING OF HIGH-VELOCITY FILTERING ELEMENTS

Fig. 4-36. High-velocity filtering elements.

The high-velocity design (Fig. 4-36a) has a packed fiber bed between two parallel screens. A multiple mounting is shown in Fig. 4-36b. Liquid flow patterns are similar to those of the low-velocity filter. This type of filter is used in the collection of sulfuric, phosphoric, and nitric acid mists and in the separation of moisture and oil from compressed gases. Relatively new applications are the collection of oil and tar mist from asphalt blowing systems, the collection of phenols from glass- and mineralfiber production, the collection of plasticizers, and the collection of soluble solids such as $(NH_4)Cl$ and $ZnCl_2$. Disposable filters are used in the recovery of platinum catalysts from nitric acid manufacture and in the collection of viruses and bacteria, and radioactive and toxic dusts.[51]

The wire mesh filter is an evenly spaced, knitted wire mesh usually mounted in horizontal beds (Fig. 4-37). The main collection mechanism is inertial impaction: rising mist droplets strike the wire, flow down the wire to a junction, coalesce, and flow to the bottom surface of the bed, where the liquid disengages as large droplets to be returned by gravity to the process equipment.[52] Factors governing maximum allowable gas velocities include gas and liquid density, surface tension, viscosity, bed specific surface area, liquid loading, and suspended solids content.[52] Advantages of wire mesh filters, as well as fiber filters, are high removal efficiency, simplicity of operation, low maintenance in dust-free service, low initial cost, and recovery of valuable products without dilution.

Baffle mist eliminators are one of the simplest devices for controlling large-diameter solid and liquid particulate emissions. A variety of designs are in use. Figure 4-38 shows the arrangement of baffles

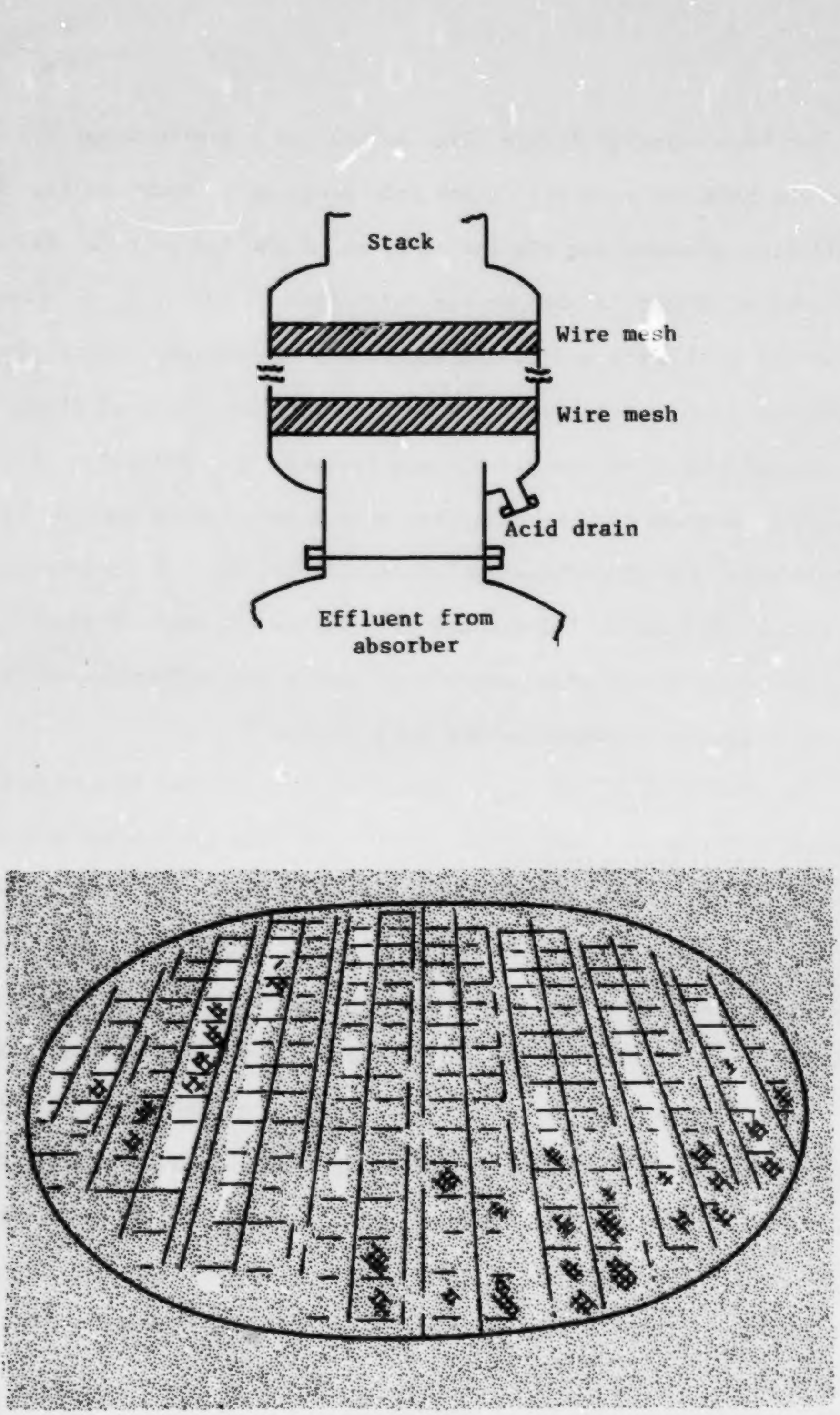
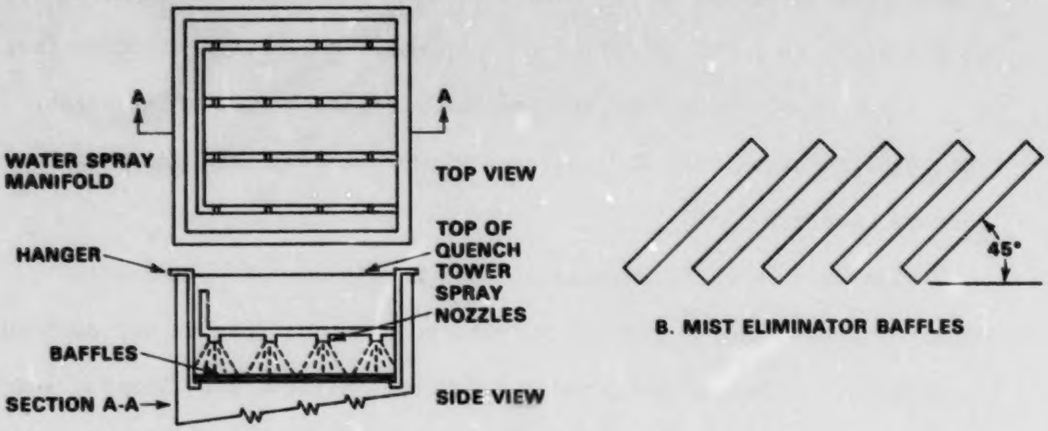

Stack
Wire mesh
Wire mesh
Acid drain
Effluent from absorber

Fig. 4-37. Wire mesh mist eliminators.


A
A
WATER SPRAY MANIFOLD
TOP VIEW
TOP OF QUENCH TOWER
HANGER
SPRAY NOZZLES
BAFFLES
SECTION A-A
SIDE VIEW
45°

A. DIAGRAM OF BAFFLE SYSTEM SHOWING CLEANING WATER SPRAYS AND BAFFLE ARRANGEMENT

B. MIST ELIMINATOR BAFFLES

Fig. 4-38. Coke quench, mist elimination baffle system.

used in the reduction of emissions from coke-quenching operations; the baffles were operated dry with short spray periods to prevent the buildup of solids.[53] Figures 4-39, 4-40, and 4-41 show layouts of mist eliminator baffles used in spray chamber scrubbers.[54,55]

Vane type mist eliminators are sometimes used instead of baffled types. The advantage of the vane type over the baffle mist eliminators is the wider range of operation at comparable collection efficiencies.[56]

Figure 4-42 shows a packed bed used for stack mist elimination. This type is often used for tail gas cleanup in sulfuric and phosphoric acid manufacture.[57-59]

Mist from bubbling solutions, such as plating baths and acid pickling baths, may be reduced by wetting agents. Foaming and nonfoaming types reduce both surface tension and bubble sizes.[60-63] Foaming agents reduce mist formation by reducing bubble escape energy and by trapping the mist particles in the foam. Nonfoamers cause smaller bubbles to escape the treated bath with less violence and thus to form fewer mist particles. Foam, which can trap hydrogen gas, can create a fire hazard and must be continually replaced.

Floating plastic objects such as polyethylene balls, hollow rods, and cylinders are also used.[64] As tank tops and mist eliminators, these reduce heat losses and ventilation requirements. In one case, 0.019 m balls covering 90 percent of the surface of sulfuric acid solutions used in the electrorefining of copper resulted in a 90-percent reduction in evaporation losses, a noticeable reduction in acid mist corrosion rates, and a 70-percent reduction in heat loss. Over a 2-week period, the reduction in loss of methylated spirits (an addition agent) paid for the balls.

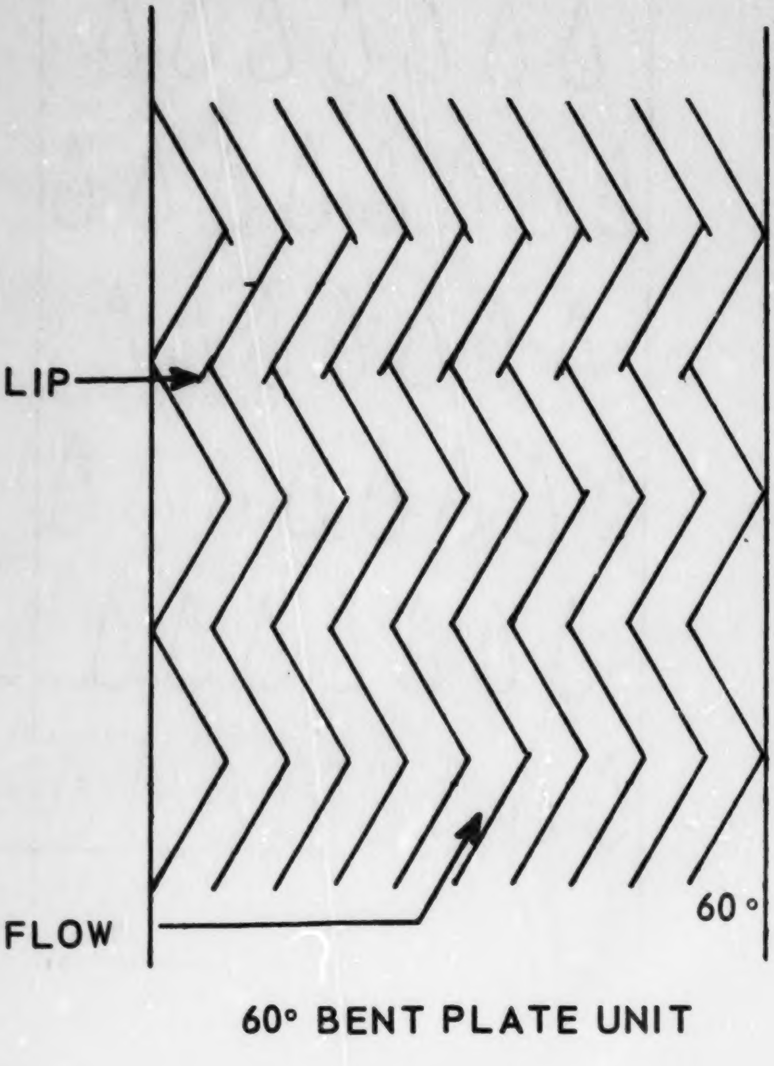

LIP
FLOW
60°
60° BENT PLATE UNIT

Fig. 4-39. Details of baffle design.

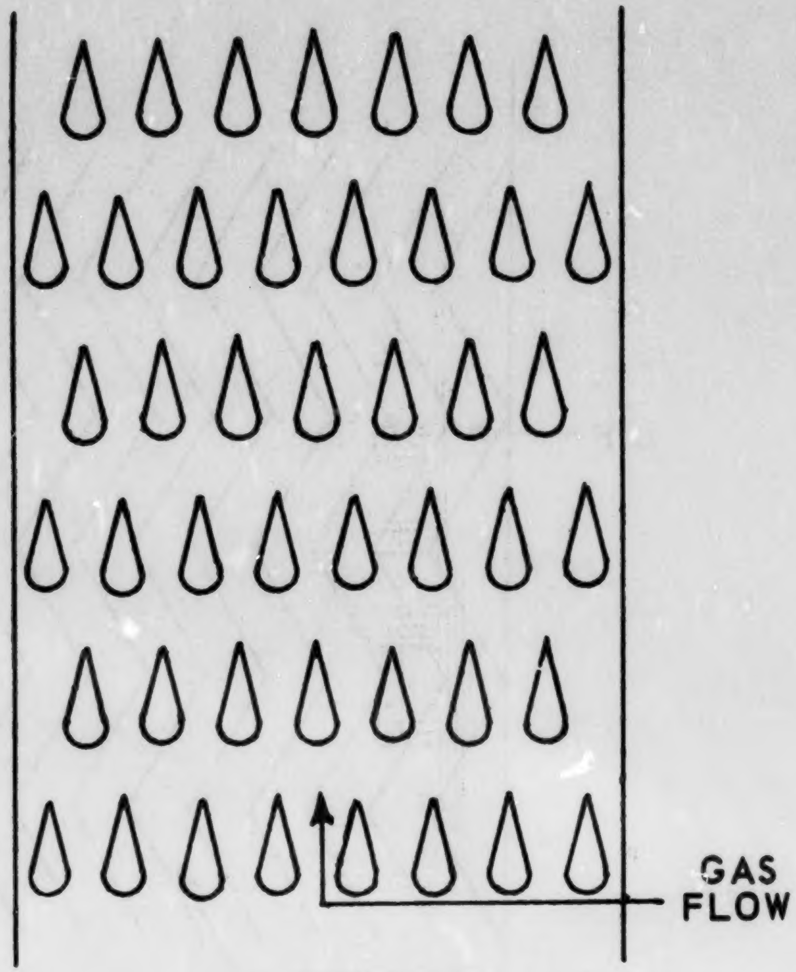


Fig. 4-40. Streamline mist eliminator baffles.

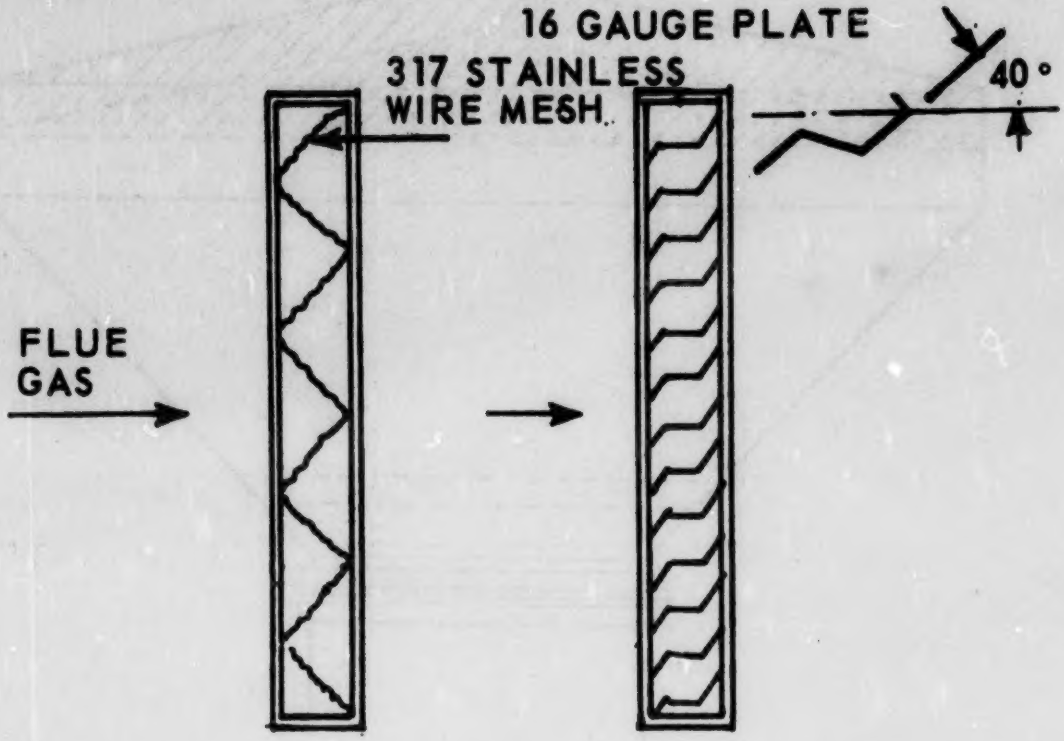

16 GAUGE PLATE
317 STAINLESS
WIRE MESH
40°
FLUE
GAS

Fig. 4-41. Screen and mist eliminator details.

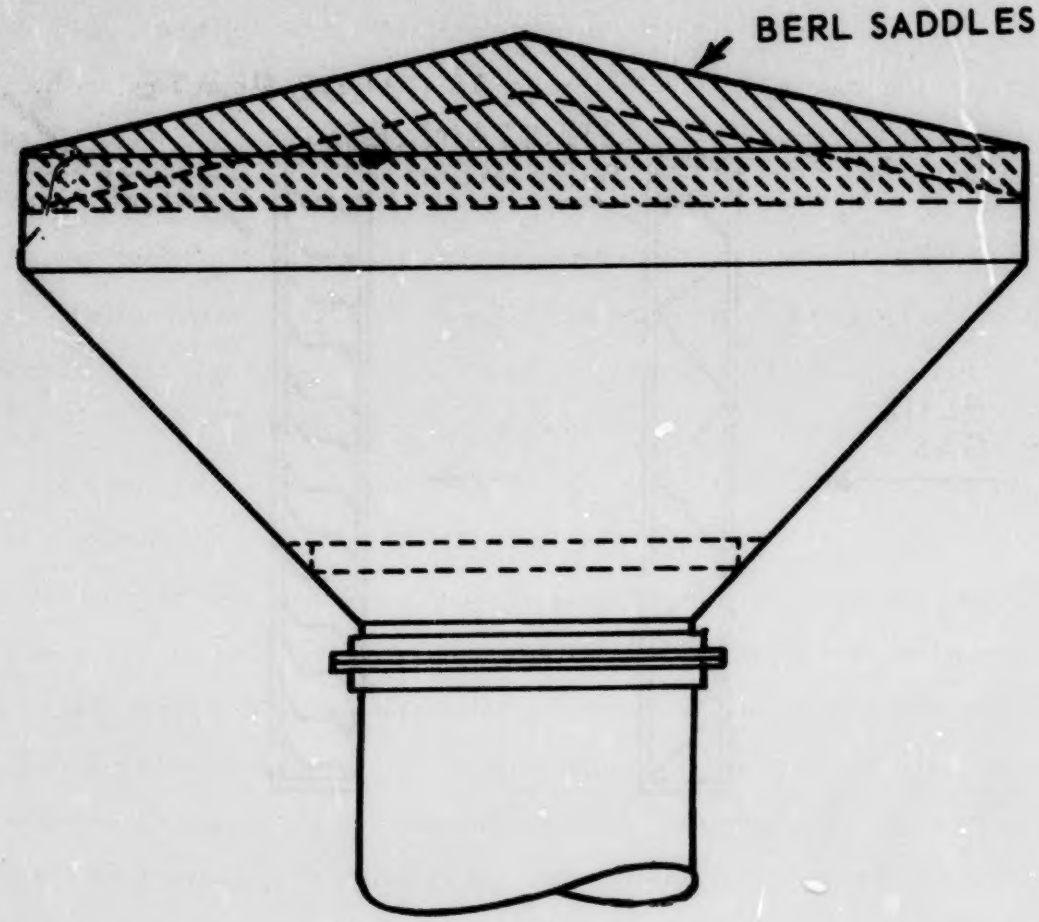

BERL SADDLES

Fig. 4-42. Bed of Berl saddles added to discharge stack.

4.3.2 Operational Factors

In the selection of a wet scrubber, water usage and waste disposal may be critical factors. Particle size distribution in the slurry, recovery value, corrosiveness of the scrubber solutions, and construction materials are important factors. Equipment for water treatment and waste disposal is discussed below. Normal operating parameters for wet collectors are shown in Table 4-10.

Settling tanks or ponds can be applied to scrubber discharges containing solid particulates. Tank or pond size can be determined by laboratory test,[76] but sedimentation techniques are usually limited either to particles larger than 1 μm or to particles that readily flocculate. Advantages are that solid waste may be sluiced to a burial pit, wastewater may be chemically treated and reused, operational costs are low, and abrasive solids can be handled. Disadvantages are that a large area is required for the settling of small particles, contamination of ground water from ponds is possible, and natural evaporation does occur.

Slurry treatment by continuous filtration is applied where the solids either have some recovery value or are porous and incompressible.[77] Advantages are a dewatered waste product and moderate space requirements. Disadvantages are high initial cost and relatively high maintenance and operational costs.

Continuous centrifuging can be applied to slurries of submicron particles as fairly high collection efficiencies.[78] The advantages are low space requirements and a large variety of designs for special requirements. Disadvantages are high capital and operating costs and susceptibility to abrasion and corrosion.

Table 4-10. - NORMAL OPERATING PARAMETERS FOR WET COLLECTORS

Type of collector	Parameter		Comments
	Pressure drop, N/m^3	Water requirement, $m^3/1000\ m^3$ gas	
Devices using energy from liquid stream			
Open spray chamber	<248.8	0.67-2.68	Large space requirement; low scrubbing efficiency for dust particles 1 to 2 µm; collection usually limited to particles 10 µm or larger.
Irrigated wet filter	49.8-748*	1.07-1.34	Gas velocity 1.02 to 1.53 m/s; bed thickness, 0.0254-0.102 m, depends on scrubber requirement.[35]
Fixed-bed scrubber:			
Crossflow	49.8-124.4	0.13-0.54	Collection efficiency ≥ 90% for particles ≥ 2 µm with dust load up to 11.4 g/m^3;[65] higher load if dust is readily soluble.
Countercurrent	124.4-248.8[38]	1.34-2.68	- - -
Cocurrent	1-4	0.94-2.02	- - -
Fluidized-bed scrubber:			
Flooded bed	996-1 490	0.268-0.34	Removal efficiency, 99% for particles ≥ 2 µm; recirculates liquid with a high solid content; handles dust load up to 91.2 g/m^3; controls acid vapor, carbon black, ceramic frit, chlorine tail gas, cupola gas, ferrite dust.[66]
Floating ball	1 490-1 990[66]	- - -	Collection efficiency > 99% for particles ≥ 2 µm;[66] liquid- and dust-handling capacity comparable to flooded-bed scrubber.[39]
Venturi jet scrubber	- - -	2.68-6.7	Energy requirement, 1 580 to 7 900 $w/m^3/s$.

*For 0.102 m bed, depending on gas loading, liquid loading, and fiber density.[35]

Table 4-10. - NORMAL OPERATING PARAMETERS FOR WET COLLECTORS - Continued

Type of collector	Parameter		Comments
	Pressure drop, N/m^2	Water requirement, $m^3/1000\ m^3$ gas	
Devices using energy from gaseous stream			
Wet cyclone:			
Tangential	324-748[49,67]	0.67-2.02	Best collection by spraying water countercurrently to gas flow in inlet duct; removal efficiency up to 96% for 2 µm and 3 µm particles.[67]
Axial flow	- - -	- - -	For final cleanup after spray dryer, calciner, cooler, crusher, classifier, and cupola.
Self-induced spray	498-3 740	0.13	Impingement velocity, 37 to 55 m/s;[67,68] chief advantage--ability to handle high dust concentrations and concentrated slurries.
Venturi scrubber	- - -	0.67-0.94	Gas velocity in throat, 61 to 183 m/s.[69]
Flooded disk	1 490-17 400	0.13	Water recirculation rate ≈ 0.67 $m^3/1\ 000\ m^3$ of gas.
Vertical venturi scrubber	- - -	0.13-0.40	- - -
Devices that add energy mechanically			
Impingement plate scrubber	249-1 990[49]	0.40-0.67[49]	Overall efficiency for a single plate, 90 to 98% for ≥ 1 µm particles.[49]
Mechanically induced spray	- - -	0.54-0.67[70]	Power requirement, 80 to 267 w/m^3.[70]
Centrifugal fan scrubber	1 620-2 240	0.101-0.201[71]	Power requirement, 1 580 to 3 160 $w/m^3/s$.[71]
Axial-fan-powered gas scrubber	1 245	- - -	Moisture removal capacity of eliminator section, sensitive to change in gas flow rate; average removal efficiency > 99% for particles 5 to 10 µm.[72]

Table 4-10. - NORMAL OPERATING PARAMETERS FOR WET COLLECTORS - Continued

Type of collector	Parameter		Comments
	Pressure drop, N/m^2	Water requirement m^3/1 000 m^3 gas	
	Devices that add energy mechanically - Continued		
Disintegrator scrubber	- - -	0.54-1.21	Power requirement, 11.1 to 17.4 kw/m^3/s; efficiency = 95% for 1-μm particles; improve by increasing either water rate or number of stator and rotor bars; efficiency independent of dust loading; exit dust concentration ≥ 9 mg/m^3.[73]
	Mist eliminators		
Low-velocity (0.026-0.153 m/s)	1 245-3 740[74]	- - -	Collection efficiency > 99% for particles < 3 μm; increase if scrubber operated below design capacity.[74]
High-velocity (2.04-2.55 m/s)	1 245-2 490[75]	- - -	Efficiency, 85 to 97% for 1- to 3-μm particles.[75]
Wire mesh	<249	- - -	Gas velocity, 3.05 to 4.57 m/s; recent development, high-energy filtration with pressure drop of 8 710 to 9 960 N/m^2.
Baffle	- - -	- - -	85 to 90% reduction for particles 70 to 1 000 μm at gas velocity up to 10.9 m/s; significant reduction in water droplet fallout.
Fiber filter	249-498	- - -	Removal efficiency up to 95% for 40-μm, spray droplets, up to a gas velocity of 7.6 m/s; velocity > 7.6 m/s causes droplet reentrainment.
Van type	25-498	- - -	Operation, 3.05 to 15.2 m/s; collection efficiency ≤ 99% for 11-μm particles.
Packed bed	- - -	- - -	Removal efficiency ≤ 65% at gas velocity of 2.13 to 3.05 m/s; mist reentrainment at higher velocity and turbulent gas flow.

The wet cyclone has been used to concentrate solids. The advantages are low initial cost, low maintenance requirements, ability to handle abrasive solids, and low space requirements. Disadvantages are the production of an overflow with high solids and relatively high power requirements.[79]

Chemical treatment of liquid waste includes the use of chlorine, lime, soda ash, carbon dioxide, amonia, corrosion inhibitors, coagulants, and/or limestone soak pits.[80-89]

4.3.3 Typical Applications

Typical applications of wet scrubbers are summarized in Table 4-11.

4.4 HIGH-VOLTAGE ELECTROSTATIC PRECIPITATORS

High-voltage electrostatic precipitators are normally used when most of the particles to be collected are smaller than 20 μm. For many operations, they are the only proven high-efficiency control devices available. A detailed study of electrostatic precipitators has been completed by Southern Research Institute.[90]

Separation of suspended particulates from a gas stream by high-voltage electrostatic precipitation require three steps:

1. Electrical charging of the suspended matter.
2. Collection of the charged matter on a grounded surface.
3. Removal of the matter to an external receptacle.

A charge may be imparted before particles enter the precipitator by flame ionization or friction; however, the bulk of the charge is applied when they pass through a high-voltage, direct-current corona.[91] Within a fraction of a second after intense bombardment with negative ions from a high-voltage electrode, the highly charged particles migrate toward a grounded collecting surface. After deposition on the surface, adhesive,

Table 4-11. - TYPICAL INDUSTRIAL APPLICATION OF WET SCRUBBERS

Scrubber type	Typical application
Spray chambers	Dust cleaning, electroplating, phosphate fertilizer, kraft paper, smoke abatement
Spray tower	Precooler, blast furnace gas
Centrifugal	Spray dryer, calciner, crusher, classifier, fluid bed process,kraft paper, fly ash
Impingement plate	Cupola, dryer, kiln, fertilizer, flue gas
Venturi:	
Venturi throat	Pulverized coal, abrasive, rotary kiln, foundry, flue gas, cupola gas, fertilizer, lime kiln, roasting, titanium dioxide processing, odor control, oxygen steelmaking, coke oven gas, fly ash
Flooded disk	
Multiple jet	
Venturi jet	Fertilizer manufacture, odor control, smoke control
Vertical venturi	Pulverized coal, abrasive manufacture
Packed bed:	
Sized	Fertilizer manufacturing, plating, acid pickling
Flooded	Acid vapor, aluminum inoculation, foundry, asphalt plant, atomic waste, carbon black, ceramic frit, chlorine tail gas, pigament manufacture, cupola gas, dryer, ferrite, fertilizer
Fluid (floating) ball	Kraft paper, basic oxygen steel, fertilizer aluminum ore reduction,aluminum foundry, fly ash, asphalt manufacturing
Self-induced spray	Coal mining, ore mining explosive dust, air conditioning, incinerator
Mechanically induced spray	Iron foundry, cupola, smoke, chemical fume control, paint spray
Disintegrator	Blast furnace gas
Centrifugal fan inline fan	Metal mining, coal processing, foundry, food, pharmaceuticals
Wetted filters	Electroplating, acid pickling, air conditioning, light dust
Dust, mist eliminator:	
Fiber filters	Sulfuric, phosphoric, and nitric acid mist; moisture separator; household ventilation; radioactive and toxic dust, oil mist,condensed organic matter, soluble solid
Wire mesh	Sulfuric, phosphoric, and nitric acid mist; distillation and absorption
Baffles	Coke quenching, kraft paper manufacture, plating
Packed beds	Sulfuric and phosphoric acid manufacture, electroplating spray tower

cohesive, and primary electrical forces must be sufficient to resist any gas stream action and secondary electrical forces that would cause reentrainment of the particles. Particulates are dislodged from the collecting surface by vibrating with rappers or by flushing with liquids; free-flowing liquids are removed by gravity.

4.4.1 Equipment Description

Two major high-voltage electrostatic precipitator configurations, the flat surface and the tube, are shown in Figs. 4-43 and 4-44. Further information on precipitator designs is in the EPA-sponsored electrostatic precipitator systems study.[90]

Uniform flow distribution is an important design factor. Perforated plates and vanes in the ductwork of the inlet and outlet help to achieve this uniform distribution. When it is necessary to install bends or elbows near the inlet or the outlet, turning vanes are helpful.

Hopper walls are sloped to promote free flow of collected material. When materials stick or bridge, vibrators or rappers can be attached at strategic locations. The hopper discharge system should minimize gas leakage into or out of the electrostatic precipitator to prevent reentrainment of the collected particulates.

A precipitator maintained and operated within design limits will perform consistently at or above design efficiencies throughout its serviceable life. Loss of efficiency is commonly caused by overloading, process changes, or inadequate maintenance. Increasing output or process gas flows without adding precipitator sections usually reduces efficiency; changes in raw materials, products, fuels, and gas stream conditions can lead to poor performance. If these possibilities are anticipated in the original design, loss of efficiency can often be avoided.

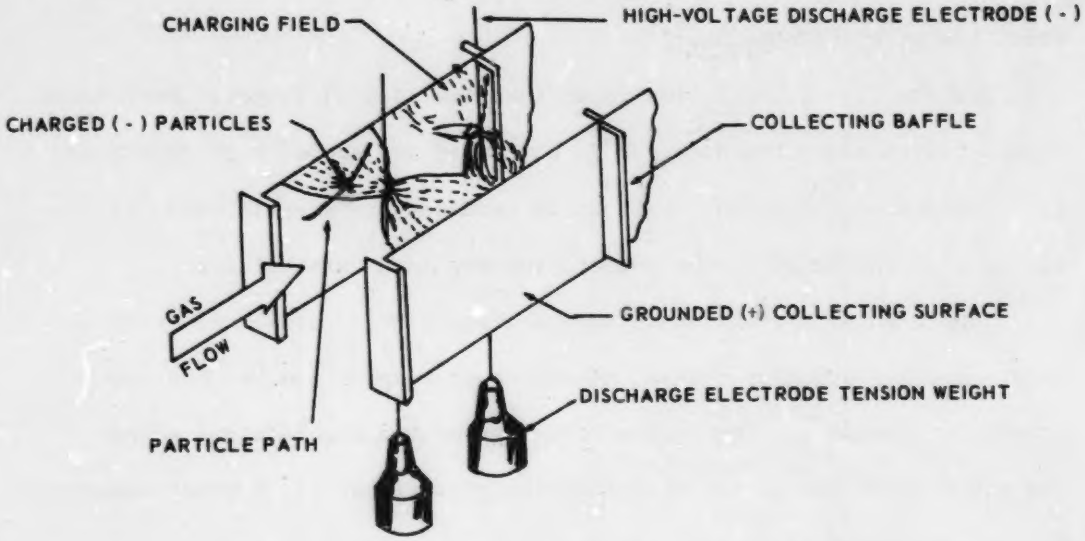

CHARGING FIELD
HIGH-VOLTAGE DISCHARGE ELECTRODE (-)
CHARGED (-) PARTICLES
COLLECTING BAFFLE
GAS FLOW
GROUNDED (+) COLLECTING SURFACE
DISCHARGE ELECTRODE TENSION WEIGHT
PARTICLE PATH

Fig. 4-43. Schematic view of a flat surface-type electrostatic precipitator.

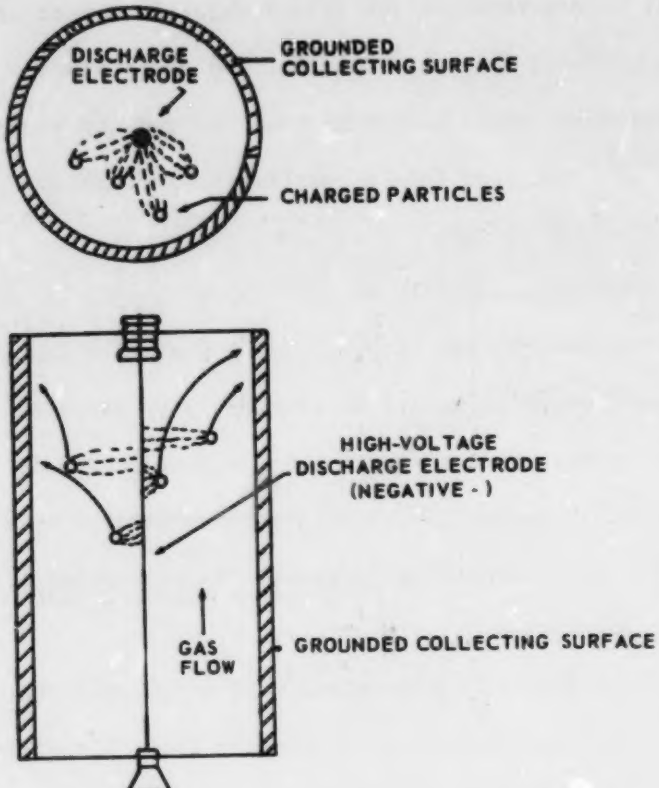

DISCHARGE ELECTRODE
GROUNDED COLLECTING SURFACE
CHARGED PARTICLES
HIGH-VOLTAGE DISCHARGE ELECTRODE (NEGATIVE -)
GAS FLOW
GROUNDED COLLECTING SURFACE

Fig. 4-44. Schematic view of tubular surface-type electrostatic precipitator.

Process changes or changes in air pollution control requirements may make it necessary to improve efficiency. Changing the voltage or power supply, increasing the number of high-voltage sections, and installing automatic power control in conjunction with increased sectionalization can improve performance. At times, efficiency may be improved sufficiently by distributing the flow more uniformly or by modification of material-handling systems. Changing the temperature of the gas stream or injecting other materials into the gas stream may improve efficiency,[92,93] but when foreign materials are injected, the air pollution aspects must be considered.

It is not always possible to anticipate changes in the properties of particulates and the gas stream. It is therefore important that collector performance be monitored frequently by sampling the inlet and outlet gas streams. When inspection and maintenance fail to bring performance to within design limits (and yet overloading is not a factor), the cause is usually traceable to changes in properties of the particulates or the gas stream.

Figure 4-45 depicts a pulverized coal-fired unit that is typical of older systems--the mechanical precleaner (multiple cyclone) and the electrostatic precipitator are downstream from the air heater. It is sometimes advisable to locate the precipitator ahead of the air heater, but at the higher flue gas temperature larger volumes of gas must be handled and additional capacity may be required.

A recent design modification introduced as a device for adding to existing installations is the grid-type precipitator,[94] in which the exhaust gas is directed through a grid of perforated plates. Charged dust particles exiting from the conventional precipitator are entrained

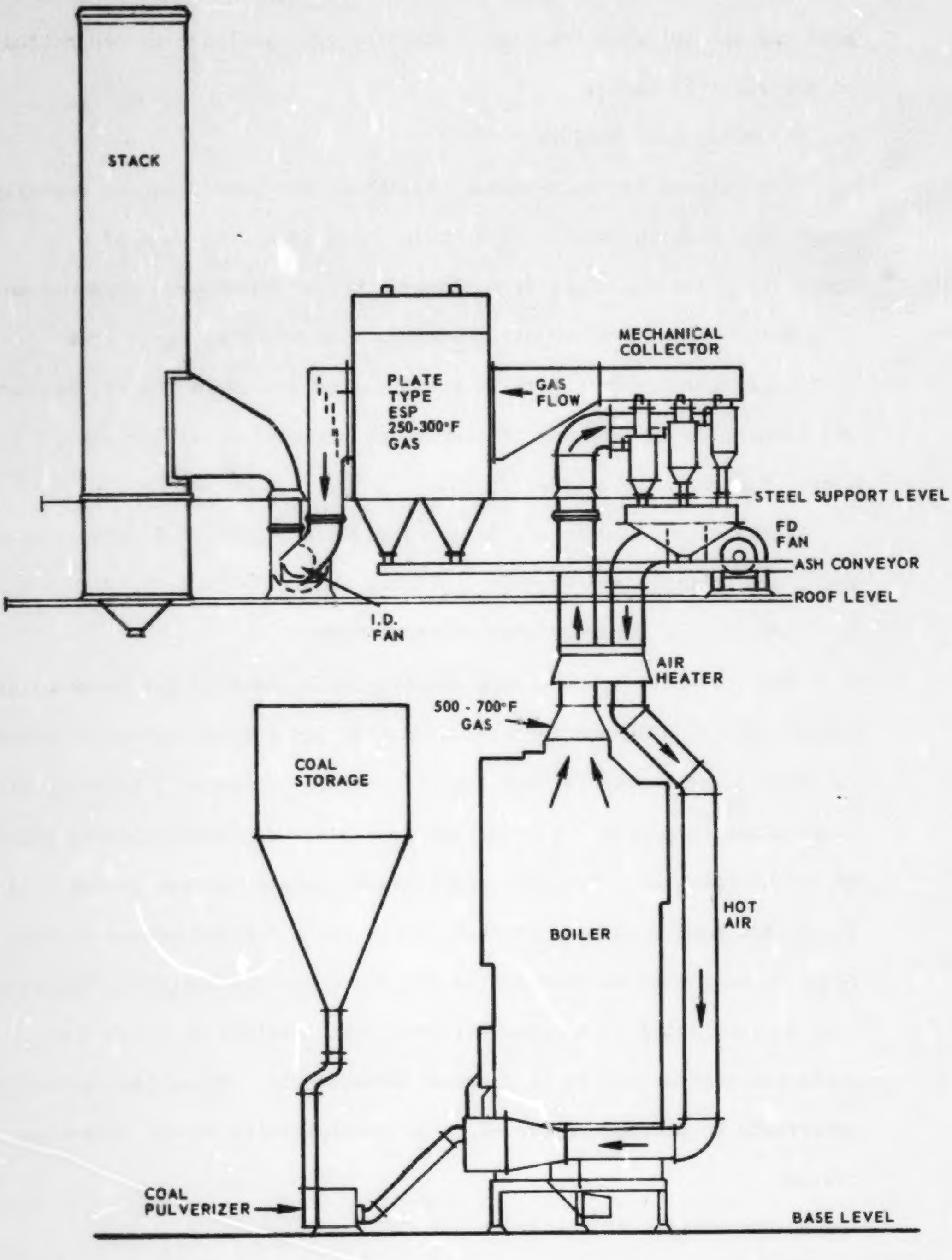

STACK
PLATE TYPE ESP 250-300°F GAS
GAS FLOW
MECHANICAL COLLECTOR
STEEL SUPPORT LEVEL
FD FAN
ASH CONVEYOR
ROOF LEVEL
I.D. FAN
AIR HEATER
500 - 700°F GAS
COAL STORAGE
BOILER
HOT AIR
COAL PULVERIZER
BASE LEVEL

Fig. 4-45. Electrostatic precipitator installed after air heater in power plant steam generator system.

into the vortices formed in the wakes of the solid portions of each grid and precipitated from there onto the grid surfaces by the action of the electric field.

4.4.2 Operational Factors

Gas volumes for high-voltage electrostatic precipitators normally range from 23.6 to 943.8 m^3/s at velocities from 0.91 to 4.57 m/s. Operating pressures range from slightly below atmospheric pressure to 1.03 MN/m^2 gauge, and operating temperatures normally range from ambient to 672 K. Peak voltage requirements are 30 to 100 kV, depending largely on the spacing of electrodes and collecting surfaces.

4.4.3 Typical Applications

High-voltage electrostatic precipitators are used to collect solid and liquid particles. Various applications are in Table 4-12.

4.5 LOW-VOLTAGE ELECTROSTATIC PRECIPITATORS

The low-voltage, two-stage electrostatic precipitator (also called an air-conditioning precipitator or electronic air filter) is used for the control of finely divided liquid particles which will drain readily from collector plates. Low-voltage precipitators cannot control solid or sticky materials, are less effective if concentrations exceed 0.91 g/m^3, and do not remove vapors. Because there are a limited number of ways of removing collected materials from the two-stage precipitator, the equipment is restricted to systems with low dust loadings in which the collector plates need to be cleaned infrequently. These limitations are deterrents to widespread use of these precipitators in air pollution control.

4.5.1 Description of Equipment

The feature of the low-voltage, two-stage precipitator (Fig. 4-46) that distinguishes it from the high-voltage unit is the ionizing zone

Table 4-12. - APPLICATIONS OF HIGH VOLTAGE ELECTROSTATIC PRECIPITATORS[90]

Application area	Dust load, g/m^3	Particle size, μm	Gas temperature, K
Electric power generation	5.56-15.95	3-15	422-533
Pulp and paper	2.28-20.5	0.4-2	380-464
Iron and steel:			
Byproduct coke gas	1.14	—	
Sinter plants	2.28	6	394-422
Blast furnaces	0.11-0.69	—	294-311
Open hearth furnaces	—	0.03-3	
Basic oxygen furnaces	34.2	0.1-1.0	394-561
Arc furnaces	—	<0.5	—
Cupolas	2.05-25.1	1-10	—
Rock products:			
Portland cement	6.85-114	—	422-645
Gypsum	9.12-127	—	325-450
Chemical industry:			
Sulfuric acid	0.46-5.7	2-3	300-356
Phosphorus	9.12-80	—	533-589
Carbon black	—	0.02-0.4	—
Municipal incinerators	—	15-30	—
Petroleum industry:			
Catalytic cracking	0.46-2.28	10-12	589-645
Detarring	--	--	294-322

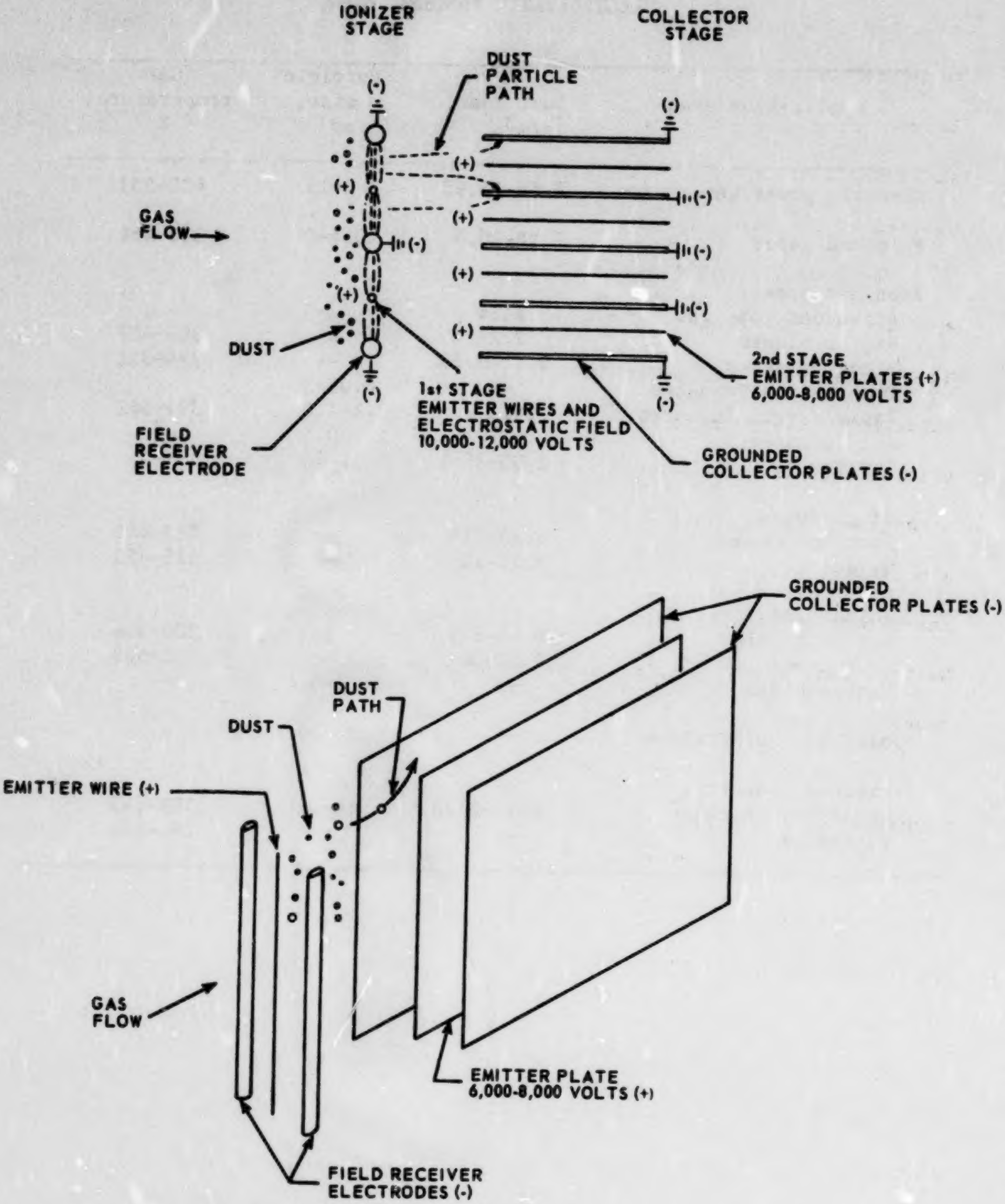

IONIZER STAGE
COLLECTOR STAGE
DUST PARTICLE PATH
(-)
(+)
GAS FLOW
DUST
FIELD RECEIVER ELECTRODE
1st STAGE EMITTER WIRES AND ELECTROSTATIC FIELD 10,000-12,000 VOLTS
2nd STAGE EMITTER PLATES (+) 6,000-8,000 VOLTS
GROUNDED COLLECTOR PLATES (-)
GROUNDED COLLECTOR PLATES (-)
DUST PATH
DUST
EMITTER WIRE (+)
GAS FLOW
EMITTER PLATE 6,000-8,000 VOLTS (+)
FIELD RECEIVER ELECTRODES (-)

Fig. 4-46. Operating principle of two-stage electrostatic precipitator.

located ahead of the collection plates.[95] The first stage, or ionizing zone, is a series of fine (177.8 μm) positively charged, equally spaced wires located 0.0254 to 0.0508 m from the parallel grounded tubes or rods; between each wire and corresponding tube is a corona which charges the particles flowing through the ionizer. The direct-current potential applied to the wires is 12 or 13 kV.

The second stage is parallel metal plates usually less than 0.0254 m apart. In some designs, alternate plates are charged positively and negatively, each to a potential of 6 or 6.5 kV, so that the potential difference between adjacent plates is 12 or 13 kV; in other designs, alternate plates are charged (6 to 13 kV) and grounded. This latter arrangement is shown in Fig. 4-46: particles enter at the left, receive a positive charge in the ionizer, and collect at the negative plates in the second stage; liquids drain by gravity to a pan beneath the plates. Neither rapping nor shaking is used, primarily because of the close spacing of plates.

The package unit shown in Fig. 4-47 collects oil mist from grinding machines.[96] Oil droplets agglomerate on the plates and drain to the bottom; but since solids or viscous liquids do not drain freely, occasional shutdown for cleaning is necessary to prevent arcing. Semiviscous materials can be collected if an adequate washing system is provided; the frequency of washing depends on the inlet loading and the characteristics of the collected particulate.

The system shown in Fig. 4-48 includes a low-pressure scrubber, a mist eliminator, and a tempering coil for pretreating and improving electrical properties before particles enter the precipitator. The scrubber removes large particles to allow longer operating periods

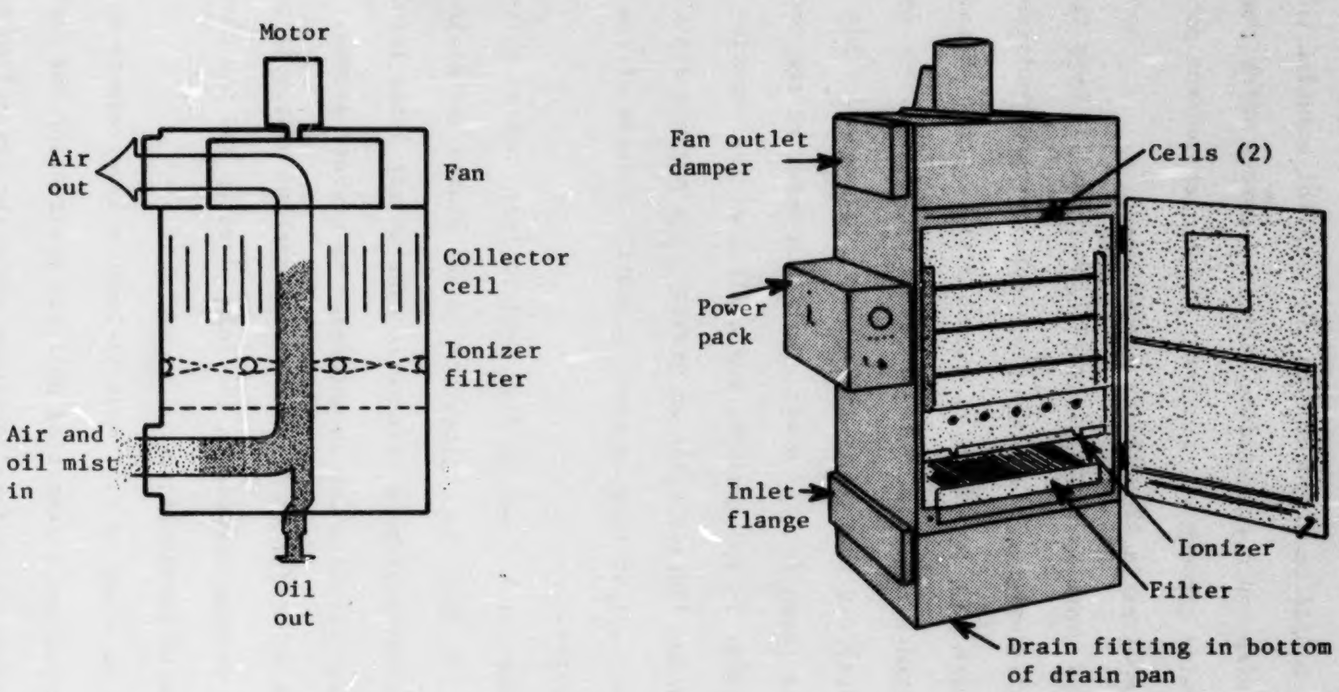

Motor
Air out
Fan
Collector cell
Ionizer filter
Air and oil mist in
Oil out
Fan outlet damper
Cells (2)
Power pack
Inlet flange
Ionizer
Filter
Drain fitting in bottom of drain pan

Fig. 4-47. Two-stage precipitator used to control oil mist from machining operations.

without shutdown for cleaning; mist eliminators remove water droplets to prevent excessive sparkover; heating coils allow flexibility in setting optimum temperature and humidity. For many materials, a relative humidity greater than 50 percent in the gas stream is beneficial.

4.5.2 Operational Factors

When a low-voltage electrostatic precipitator is used with air-conditioning, velocities range between 1.5 and 3 m/s. However, for pollution control where the particulate loadings are high, the superficial gas velocity through the plate collector section should not exceed 0.52 m/s. The upper limit for streamline flow through two-stage precipitators is 3 m/s, but mechanical irregularities in units now being manufactured may reduce this upper limit.

The effect of gas velocity on collection efficiency for several industrial operations is shown in Fig. 4-49. Efficiencies of 80 percent and greater are shown for the collection of oil mist at asphalt paper saturators and for air-conditioning applications. From 60 to 80 percent is possible for meat smokehouses at a velocity of 0.46 m/s, but efficiency decreases rapidly at higher velocities. Test data for typical installations are shown in Table 4-13.

The practical voltage limit for ionizing in low-voltage precipitators is 18 kV; most units operate at 10 to 13 kV. Without a corona between the plates, current flow is small (4 to 10 mA). Collecting plates are usually energized at 5.5 to 6.5 kV, but potentials up to 13 kV are possible. The degree of ionization may be increased by increasing the number of ionizing electrodes--either by decreasing spacing or by installing a second set of wires in series. Because decreased spacing

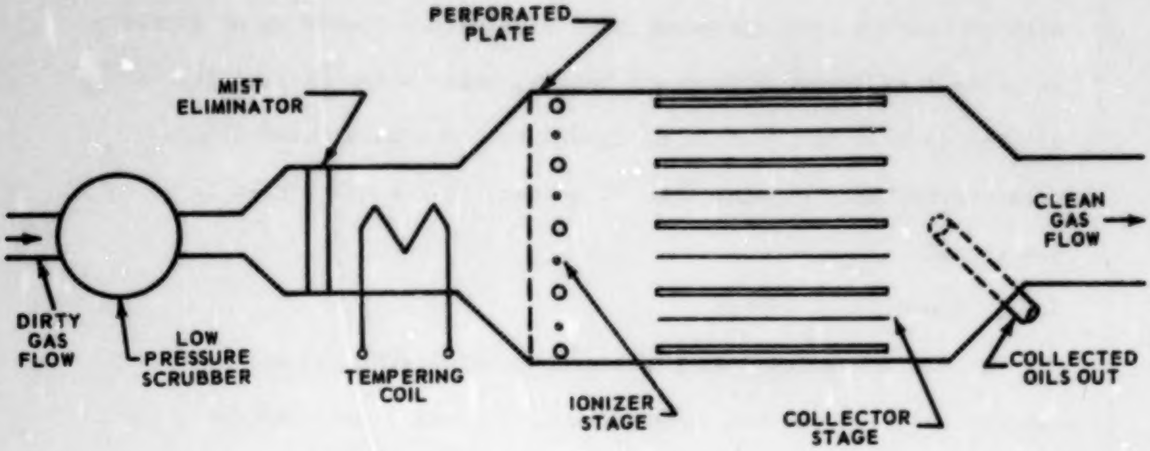

PERFORATED PLATE
MIST ELIMINATOR
CLEAN GAS FLOW
DIRTY GAS FLOW
LOW PRESSURE SCRUBBER
TEMPERING COIL
IONIZER STAGE
COLLECTOR STAGE
COLLECTED OILS OUT

Fig. 4-48. Two-stage electrostatic precipitator with auxiliary scrubber, mist eliminator, tempering coil, and gas distribution plate (top view).

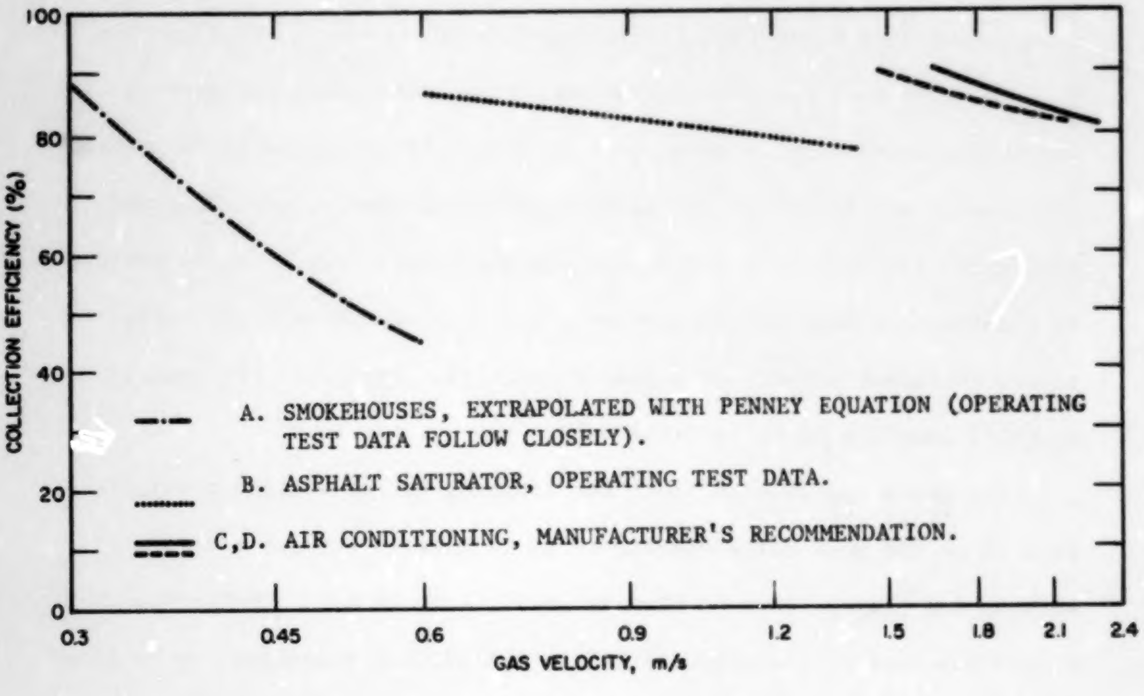


Fig. 4-49. Efficiency of two-stage precipitator as function of velocity for several industrial operations.

Table 4-13. - INDUSTRIAL OPERATION OF TWO-STAGE PRECIPITATORS[95]

Contaminant source and type	Ionizing voltage, V	No. of ionizer banks	Collector voltage, V	Efficiency, wt percent	Velocity, m/s	Inlet conc., g/m^3
Tool grinding--oil aerosol	13 000	1	6 500	90	1.7	-----
Meat smokehouse--wood smoke, vaporized fats	13 000	2	6 500	90	0.31	0.24
Meat smokehouse--wood smoke, vaporized fats	10 000	1	5 000	50	0.26	2.73
Deep-fat cooking--bacon fat aerosol	13 000	2	6 500	*	0.35	-----
Asphalt saturator (roofing paper)--oil aerosol	12 000	1	6 000	85	0.74	0.88
Muller-type mixer--phenol-formaldehyde resin	13 000	1	6 500	87	0.38	0.11

*75 percent opacity reduction.

requires reduced voltage to prevent sparkover, there appears to be an advantage in the series arrangement. Decreased spacing, however, lowers the initial cost and the space requirements.

Low-voltage precipitators of standard design for capacities up to 9.4 m^3/s are supplied by manufacturers in preassembled units requiring only external wiring and dust connections. The installed weight is approximately 390.4 kg/m^2 of cross-sectional area measured perpendicular to the gas flow, and the airflow is about 0.51 m/s. In these standard units, collector cells usually are made of aluminum, and the housing is made of galvanized steel with aluminum frames. Where washing is to be frequent and even mildly corrosive conditions exist, ionizer wires should be made of stainless steel.

Precipitators installed in positions requiring abrupt changes in gas flow preceding the unit can experience turbulent, uneven flow with high local velocities, which lead to low overall efficiencies. If a straight section of at least eight duct diameters is not available ahead of the precipitator, mechanical means must be used for balancing the airflow. Several types of distribution baffles and turning vanes have been devised, but perforated sheet metal screens with about 40 percent open area are effective.

To assure optimum performance, the internal parts of the precipitator must be clean, and the plate and wire spacings must be maintained within reasonably small tolerances. The frequency of internal washing depends on the application. High particulate loadings in the gas stream and sticky materials are the greatest problems; in contrast, two-stage precipitators can operate indefinitely where relatively clean, free-flowing oils are collected.

4.5.3 Typical Applications

Applications of low-voltage precipitators to air pollution control have developed slowly since 1937, when the first installation was successfully used to collect ceramic overspray from pottery-glazing operations. Other applications are the collection of oil mist from high-speed grinding machines and the cleaning of gases from deep fat fryers, asphalt saturators, rubber-curing ovens, and carpet mill dryers.

High-speed grinding machines generate mist from cutting oils which must be vented from the working area. Precipitator package units of the type shown in Fig. 4-47 collect the mist; the filter ahead of the precipitator removes metal chips and any other large particles. Concentrations of solids and tars are usually low enough to be flushed from the plates along with the collected oil droplets.

In the manufacture of roofing paper, low-voltage electrostatic precipitators remove the steam-distilled organic materials from hot liquid asphalt. Moisture evolved from the paper carries oil from the process. Oils that are collected flow readily from the plates of the electrostatic precipitator; only occasional cleaning is required.

Smokehouses are used by meatpacking houses to cook and smoke a variety of products; during the cooking, exhaust products are reasonably innocuous, so exhaust gases can be discharged directly to the atmosphere, but smoke generated from hardwood sawdust contains liquid aerosols (mostly partially oxidized organics) and odorous, eye-irritating gases and vapors. Two-stage precipitators, used with limited success to control visible aerosols from smokehouses, use the design of Fig. 4-48 with a scrubber, mist eliminator, and tempering coil. Under optimum operation, these units reduce visible emissions (tars and gums) to about

10-percent opacity, but maintenance is a problem and the exhaust gases remain odorous and lachrymose. When the unit is warm (322° to 356° K), at least some of the tars drain from the plates. If the plates are not cleaned regularly, arcing occurs in the collector section, particularly near the lower edges of the plates.

Two-stage precipitators offer the promise of low-cost control for oil mists generated by operations such as rubber curing and carpet mill drying. Conceivably, these devices can be used wherever other considerations, such as odors and eye irritants, are not problems.

4.6 FABRIC FILTERS

4.6.1 Theoretical Principles

One of the oldest, most effective devices for removing solid particulate contaminants from gas streams is filtration through fabric.[97] The fabric filter is capable of high-efficiency collection for particles as small as 0.01 μm.[98]

When dust-laden gas is passed through a fabric filter, the particles are retained on the upstream or dirty-gas side of the fabric, and the gas passes through it to the downstream or clean-gas side. Dust is removed from the fabric by gravity and by mechanical means.[99,100]

4.6.1.1 Mechanisms of Filtration--Particulates leave the airstream or gas stream by impinging on and adhering to the fibers,[101,102] which are usually woven with relatively large open spaces, sometimes 100 μm or larger. High collection efficiency for dust particles 1 μm or less has been achieved, thus the filtering process is not simple fabric sieving. Initially, small particles are retained on the fiber by direct interception, inertial impaction, diffusion, electrostatic attraction, and gravitational settling; when a mat or cake of dust has accumulated, more particles are collected by mat or cake sieving as well as by the above mechanisms; periodically, the accumulated dust is removed, but residual dust remains and aids further filtering. A simple method of estimating the relative importance of the various filtration mechanisms is shown in Table 4-14.[103]

Direct interception--Airflow in fabric filtration is usually laminar.[104] When the fluid streamline carrying the particle approaches a filter element to within a distance less than one-half the particle diameter, the particle is directly intercepted. If the particle has a very small mass, it will not deviate from the streamline and will adhere to the element. (See path A in Fig. 4-50).

Inertial impaction--When the mass of the particle is so great that it is unable to follow the streamline around the filter element, the particle continues along a path of less curvature.[105] It comes closer to the element than if it had followed the streamline. (See path B in Fig. 4-50.) Impaction is significant for the collection of 2-μm particles and it is the predominant mechanism for larger particles.[106]

Diffusion--For particles less than 0.05 μm, diffusion is the predominant mechanism. Such small particles do not follow the streamline because Brownian motion increases the chance of contact between the particles and the collection surfaces. A concentration gradient, established after the collection of a few particles, increases the rate of deposition. Low air velocity increases the time for contact.[106]

Electrostatic attraction--Electrostatic attraction, which draws particles and filter element together whenever either or both possess a static charge (path C, Fig. 4-50), affects particle agglomeration, fabric cleanability, and collection efficiency. This force is either direct,

Table 4-14. - CONTROL MECHANISM FOR PARTICLE SIZE COLLECTION[101]

Primary collection mechanism	Diameter of particle, μm
Direct interception	>1
Impingement	>1
Diffusion	0.001 to 0.5
Electrostatic	0.01 to 5
Gravity	>1

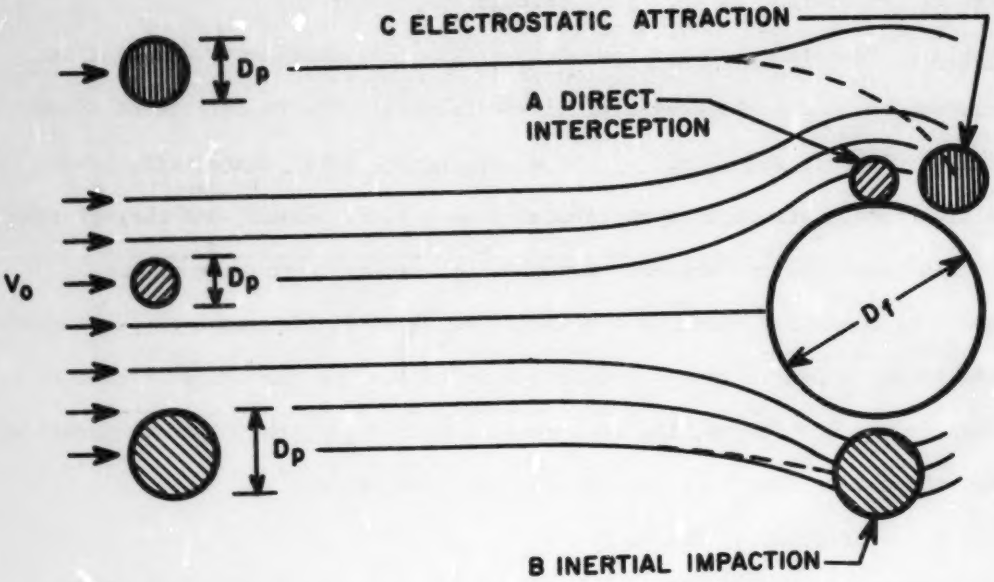

C ELECTROSTATIC ATTRACTION
D_p
A DIRECT INTERCEPTION
V_o
D_p
D_f
D_p
B INERTIAL IMPACTION

Fig. 4-50. Streamlines and particle trajectories approaching filter elements. (D_f represents the filter element diameter; D_p, the diameter of the particles; V_o the velocity of the gas stream.)

when both particle and filter are charged, or induced, when only one is charged. Charges are usually introduced during the manufacture of the fiber. A triboelectric series can be useful in selecting filter fabrics with desirable electrostatic properties.[107]

Gravitational settling--Gravity may cause particles to settle on the filter surface as they pass through the filter.

4.6.1.2 Resistance to Airflow--Both clean cloth resistance and dust mat resistance affect the design of fabric filters. The resistance of clean filter cloth is determined by the weave and the fiber characteristics. A tight weave offers more resistance than a loose weave. One characteristic is permeability--the air volume (m^3/s) passing through a square meter of clean new cloth at a standard pressure differential of 124.4 N/m^2. The pressure drop across the dust mat is related to the concentration of dust in the gas stream, the mass density of the gas, the time of operation, and the face velocity of the gas through the fabric.

4.6.2 Description of Equipment

Three baghouse designs--open pressure, closed pressure, and closed suction--are used for fabric filters.[108] Generally, the design is dictated by the moisture in the waste gas. The higher the dewpoint, the greater the need to prevent condensation, which can moisten the filter cake, plug the cloth, and corrode the housing and hoppers.

An open pressure baghouse, constructed with corrugated steel or asbestos cement walls, with the fan on the dirty-gas side of the system, can be operated with open sides if it is protected from the weather. Because the cooling is facilitated, hot inlet gas and low temperature filter media can be used.[106] On the other hand, blower wear is high since the blower must handle the entire dust load. Figures 4-51 and 4-52 illustrate the open pressure baghouses.[108,109]

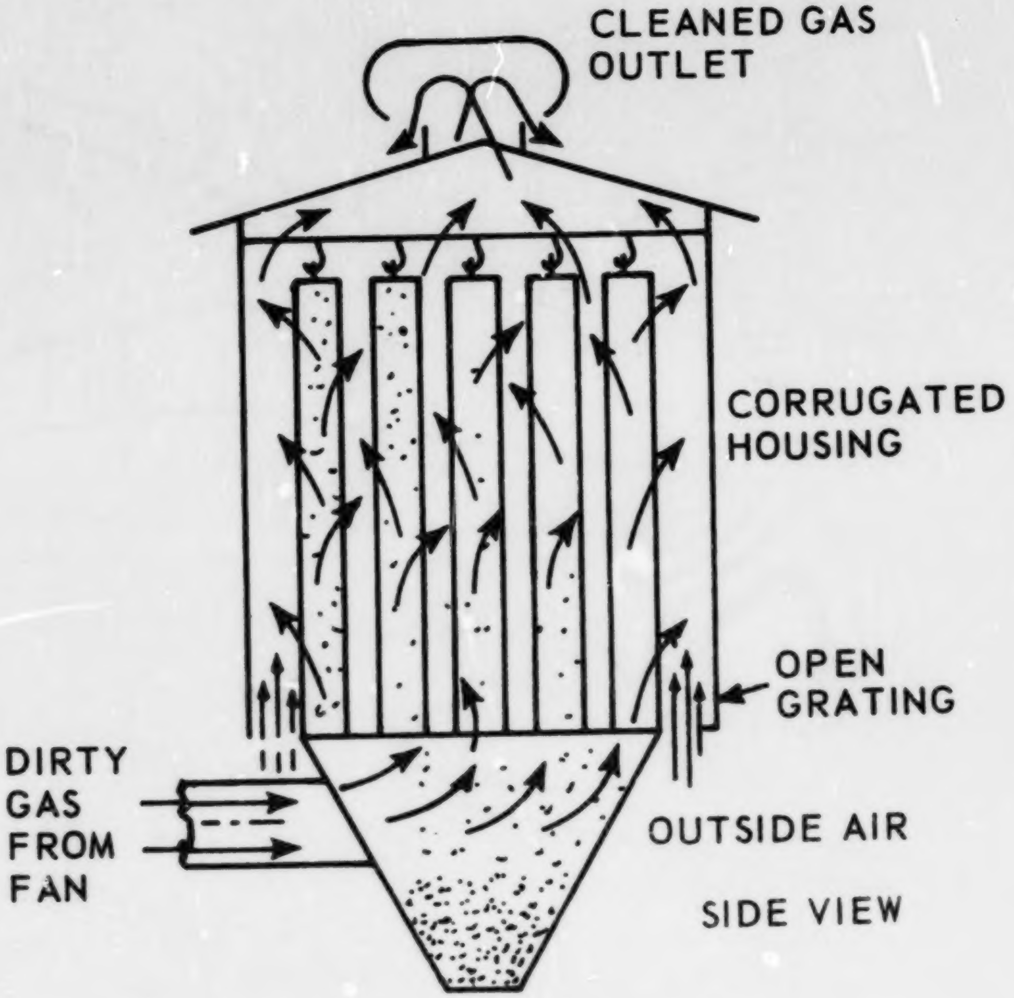

CLEANED GAS OUTLET
CORRUGATED HOUSING
OPEN GRATING
DIRTY GAS FROM FAN
OUTSIDE AIR
SIDE VIEW

Fig. 4-51. Open pressure baghouse.

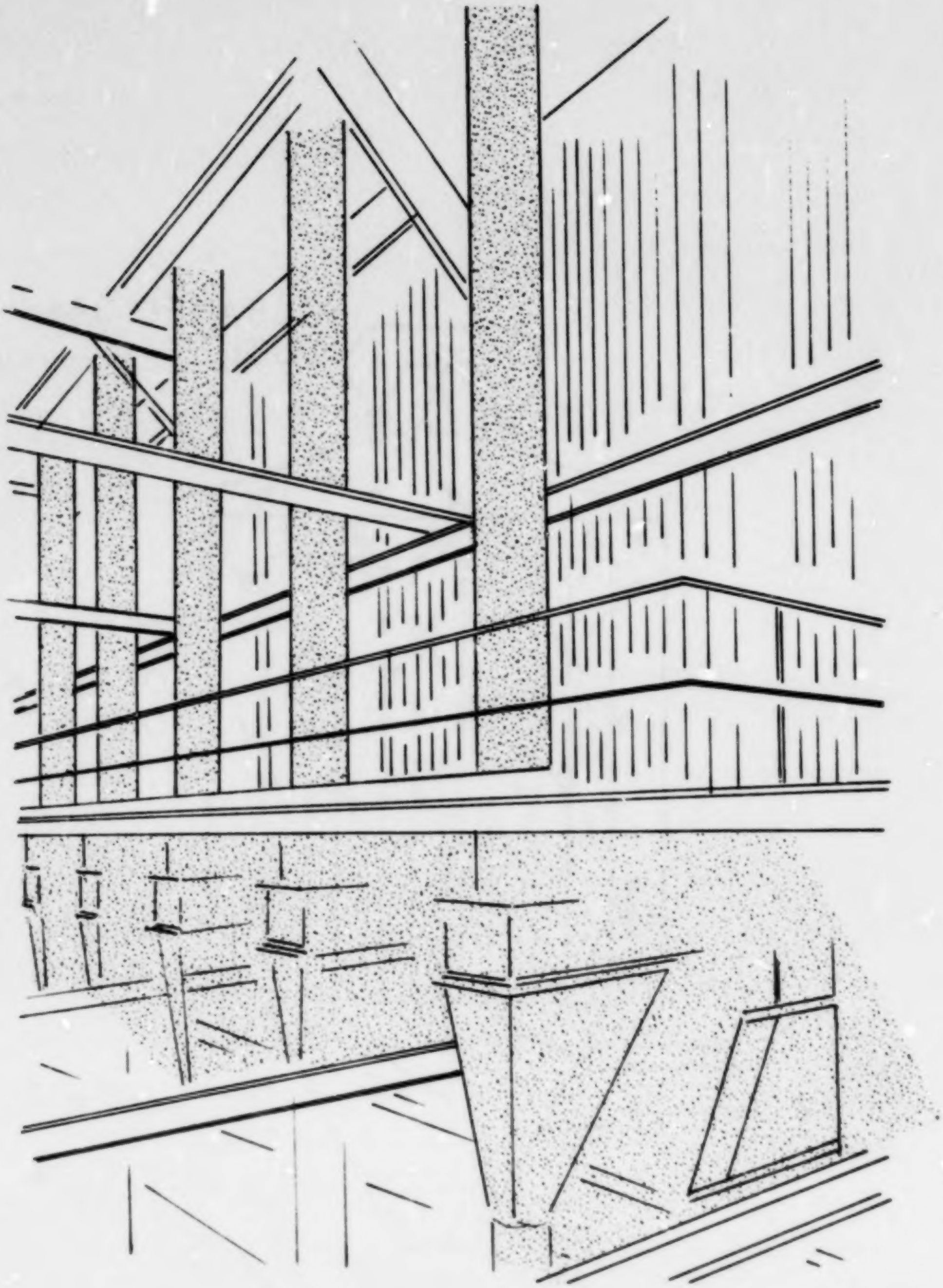


Fig. 4-52. Open pressure baghouse unit showing installation without a separate clean-gas housing.

A closed pressure baghouse, often constructed with asbestos cement walls, also has the fan on the dirty-gas side of the system, but the sides are closed, the floor is closed, and the hoppers are insulated. The closed unit is used for gases with high dewpoints and for toxic gases that cannot be released at low elevations. Blower wear and maintenance problems are identical to those of the open pressure baghouse. Figures 4-53 and 4-54 illustrate the closed pressure baghouse.[108,109]

A closed suction baghouse has the fan on the clean-gas side of a welded, airtight structure; the floor is closed; and the walls and hoppers are insulated. This type is used for gases with dewpoints between 347° and 356° K. Metal used to construct the baghouse walls and hoppers must be strong enough to withstand the pressure differentials; a differential of several cm of water can result in large forces because of the large wall areas.[106] Blower maintenance is cheaper because the blower is on the clean-gas side of the system, but inspection of the bags is difficult. Figure 4-55 illustrates the closed suction baghouse.[108,109]

For all baghouses, easy access must be provided to change bags and to perform maintenance. To permit bag changing without taking the unit off stream, many units have internal partitions so an individual compartment can be isolated and maintained while other compartments continue to filter.

Baghouses are supplied as self-contained units or as field-erected control systems. In manufacturing plants where few dust sources need control, the individual fabric collector has several advantages over a large central collecting system:[110] the self-contained unit collector is shipped erected (or nearly so), can be installed with minimum ductwork, and can be moved to sites requiring dust control for idle batch processes. The central collecting system not only requires considerable

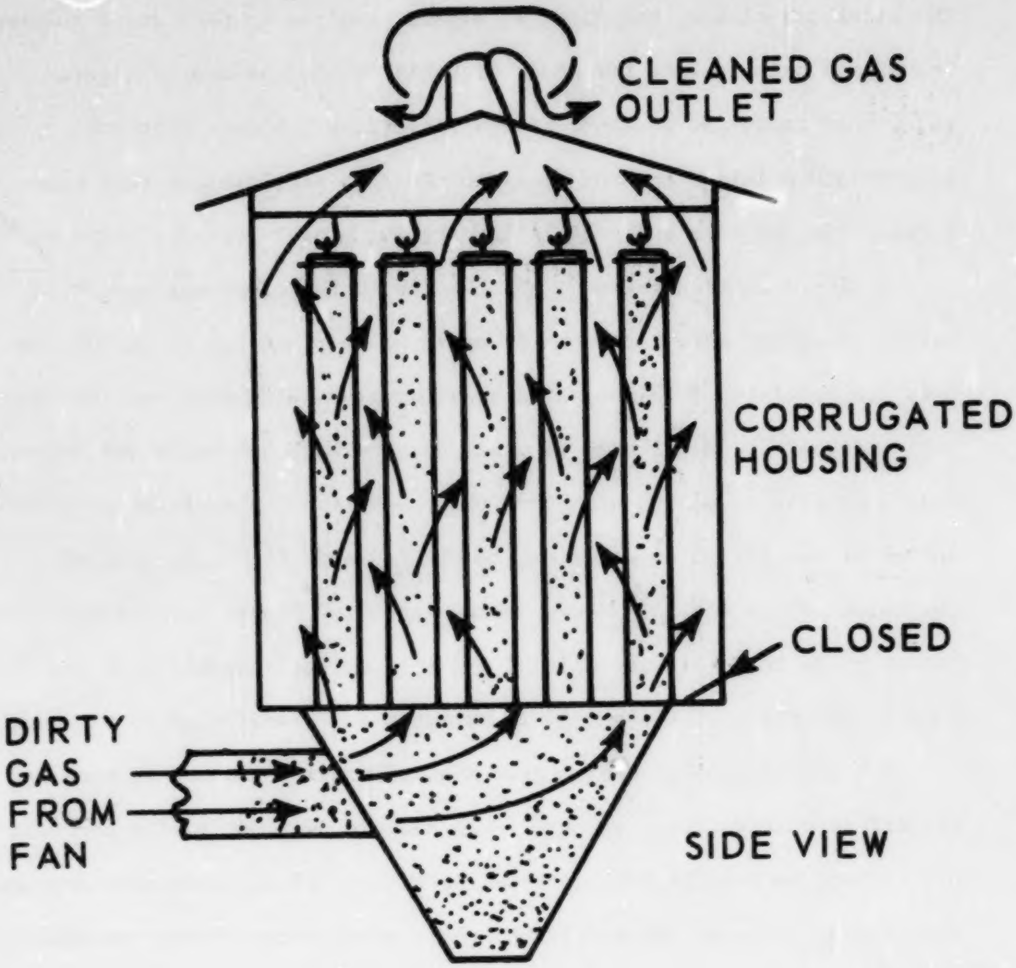

CLEANED GAS OUTLET
CORRUGATED HOUSING
CLOSED
DIRTY GAS FROM FAN
SIDE VIEW

Fig. 4-53. Closed pressure baghouse.

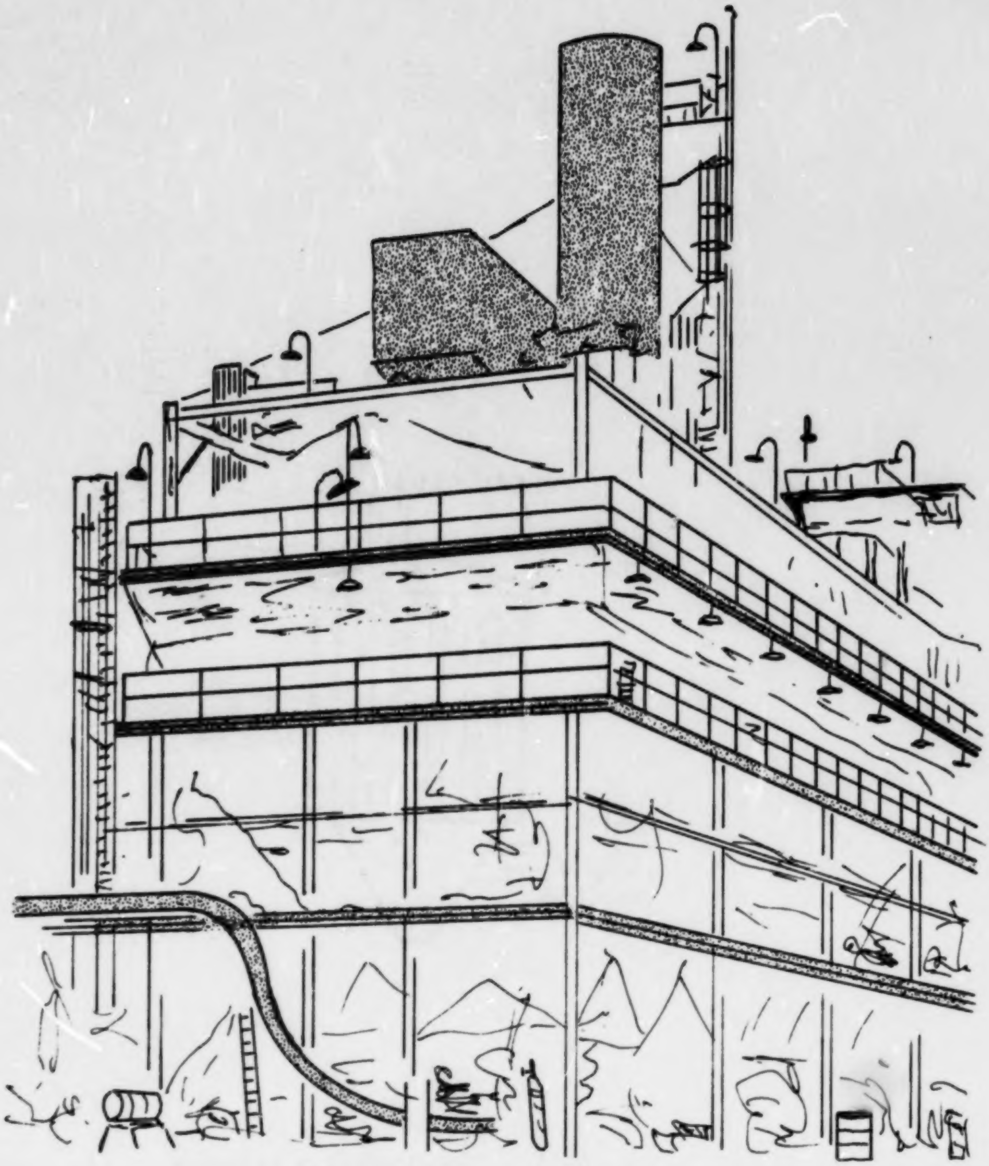


Fig. 4-54. Closed pressure baghouse unit.

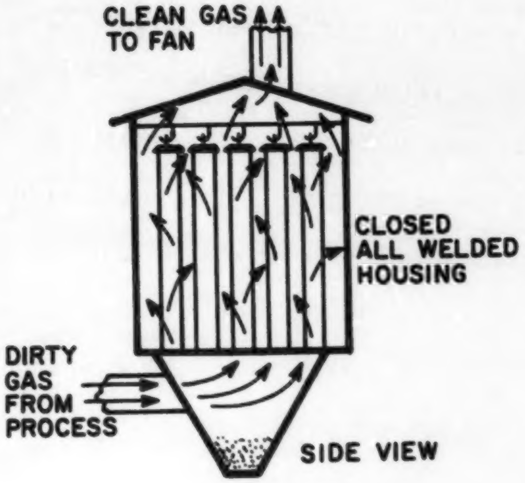

CLEAN GAS
TO FAN
CLOSED
ALL WELDED
HOUSING
DIRTY
GAS
FROM
PROCESS
SIDE VIEW

Fig. 4-55. Closed suction baghouse.

floor space, it is often erected outdoors and thus may require insulation and even supplementary heat to avoid chilling the gas to the dewpoint; however, this system is preferred in large manufacturing plants where many dust sources of continuous processes must be controlled.

4.6.2.1 Bag Shapes--Two major bag shapes are the envelope (flat) and the tube. In the envelope, illustrated in Fig. 4-56,[109] dust is collected on the outside of the bag, which contains screens or frames to keep it from collapsing. The internal screen complicates bag changing and, due to its contact with the fabric, reduces cloth life; however, the envelope bag has two advantages over the tube bag: it provides more filtering surface per volume and, if the dust has a tendency to bridge, every other bag may be removed to prevent plugging.

One design for the tubular bag, illustrated in Fig. 4-57, is open at one end and closed at the other.[109] The unibag is not attached to other bags. The multibag, three or six tubular bags sewn together as shown in Fig. 4-58,[109] is limited to a top loop suspension and thus requires adjustment occasionally because of dimensional instability.

In the multibag and unibag filters that are in widespread use, airflow may be either from the outside or the inside. Feed to the bags can be from the bottom or the top. Bottom entry allows preseparation of coarse particles in the hopper, so the fabric handles only the suspended dust; top entry not only forces the dust load to pass through the entire tube before it reaches the hopper but also creates a dead gas pocket in the hopper that can collect condensation from moisture-laden gases.

4.6.2.2 Cloth Types--The two basic types of cloth used in fabric filters are woven cloth ("cake" filter media) and felted cloth ("fiber" filter media).[111,112] Clean felted cloth is a more efficient dust collector

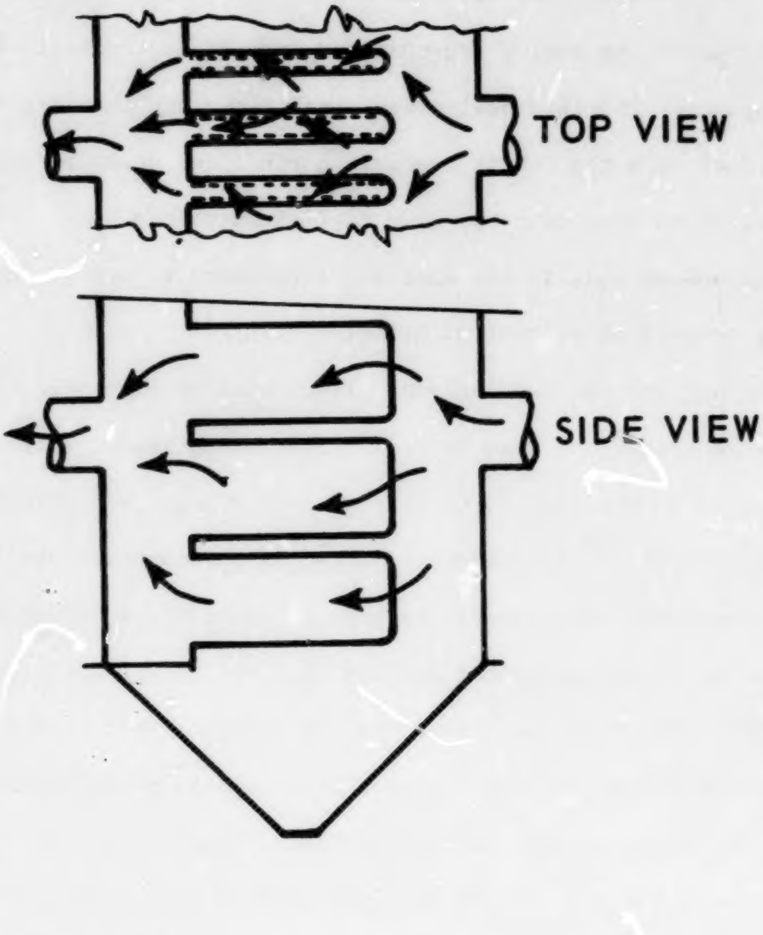

TOP VIEW
SIDE VIEW

Fig. 4-56. Typical flat or envelope dust collector bag.

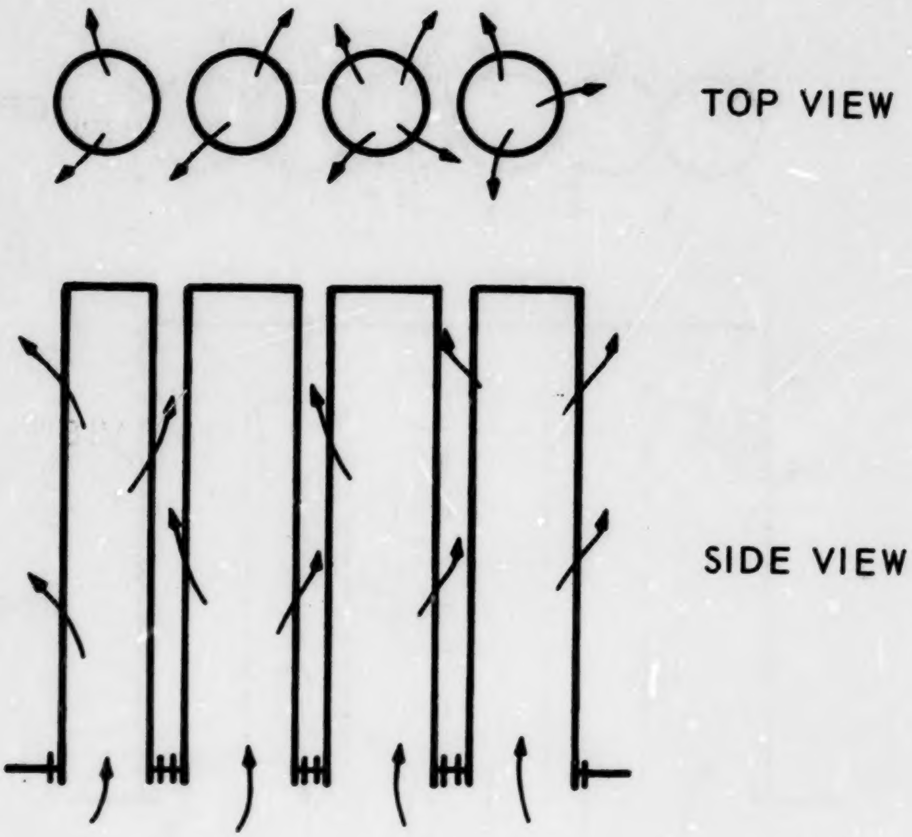

TOP VIEW
SIDE VIEW

Fig. 4-57. Typical round or tubular dust collector bag.

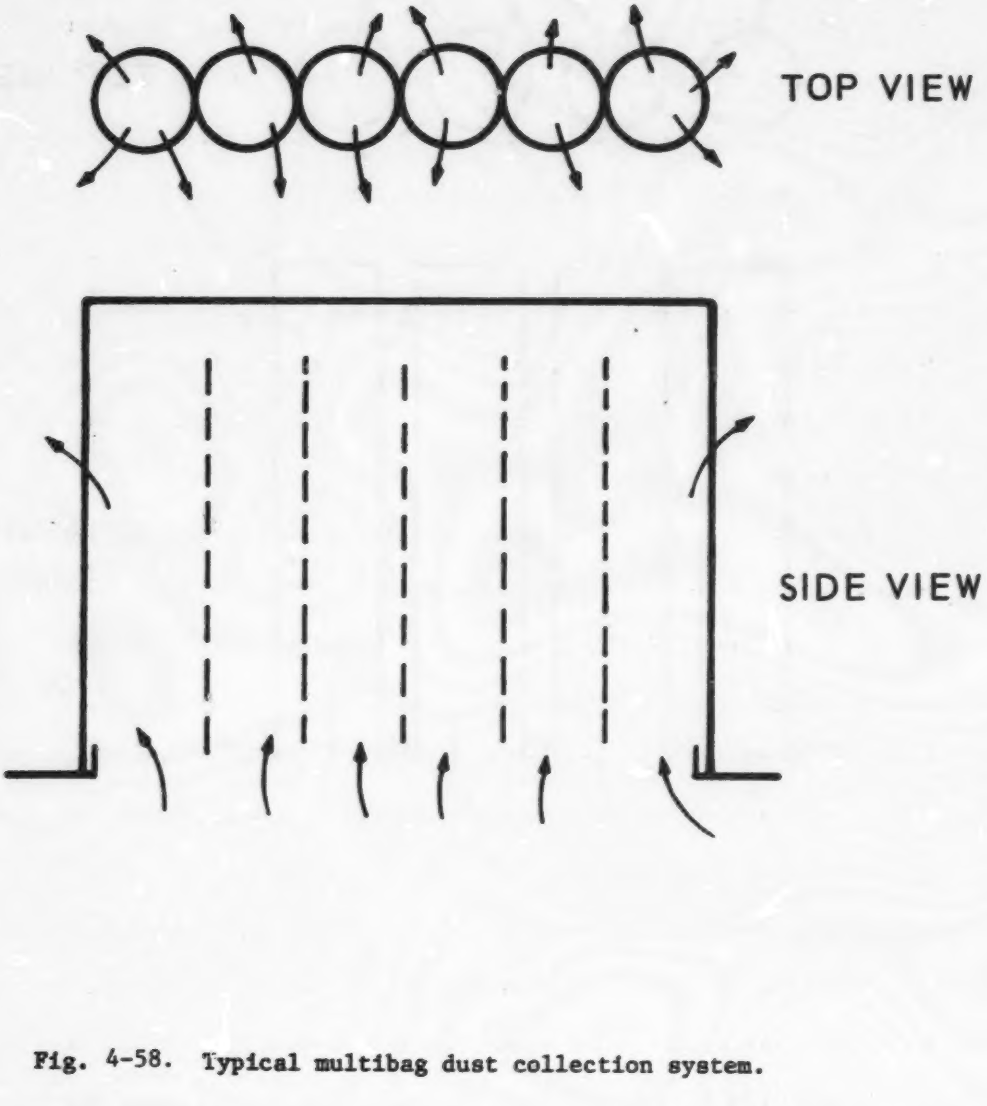

TOP VIEW
SIDE VIEW

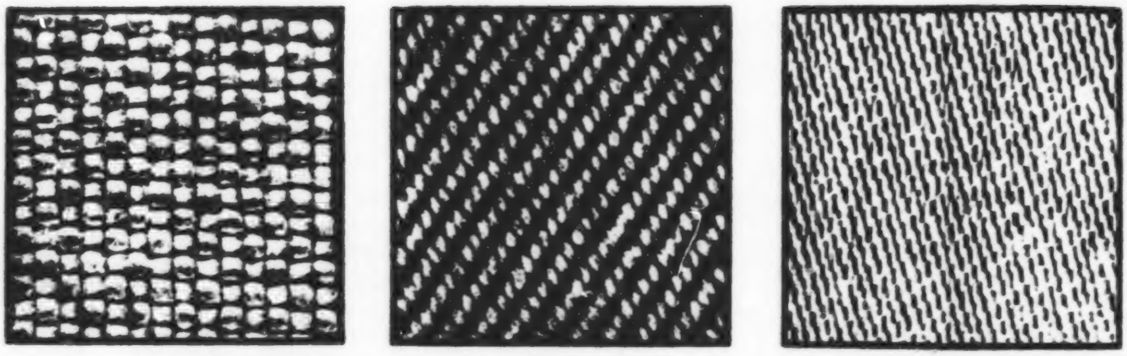
Fig. 4-58. Typical multibag dust collection system.

than clean woven cloth, but efficiencies are equivalent after a dust layer accumulates on the surface of the woven cloth.

Woven fabrics--Woven fabric filters in conventional baghouses usually have filtering velocities of 0.0051 to 0.0255 m/s.[105,113] Porosity is varied by using different fabric counts, yarns, cloth weights, and weave patterns. The count is the number of warp (lengthwise) and fill (crosswise) yarns per unit length in a woven fabric. The three forms of yarn used are monofilament, multifilament, and spun-staple:[112] monofilament is a synthetic fiber made in a single, continuous filament; multifilament is two or more monofilaments twisted together; spun-staple is short lengths of natural or synthetic fiber twisted into a continuous strand. Woven fabric bags are made from cotton, wool, Dacron, nylon, Orlon, Nomex, polypropylene, Teflon, and fiberglas. The filter media Redon, Orlon, Dralon T and Dolan can be used in neutral as well as weak acid or basic atmospheres up to temperatures of 413 K.

Porosity can be decreased by weaving cloth from napped yarn or plied yarn. Napped yarn is made by abrading the surface of the filament yarn to produce a fuzzy, fibrous condition;[114] plied yarn is made by twisting lighter weight yarns together in a single, continuous strand.[115] For example, an 800-denier fabric (denier is g/1 000 m) may be woven from plied yarn made by twisting four strands of 200-denier yarn to increase its dust retentivity without changing the weight of the cloth.

The basic weave patterns are plain, twill, and sateen,[115] as illustrated in Fig. 4-59. The plain weave, common in certain cotton ducks and many synthetic fibers,[115] has a simple "one up and one down" construction, which permits maximum yarn interlacing; tight weaving leads to low permeability, and lowered counts enable this weave to be as open



PLAIN

TWILL

SATEEN

Fig. 4-59. Basic fabric weaves used for woven filter bags.

as desired. The twill weave, for cotton and synthetics,[115] has sharp diagonal lines formed by passing a warp yarn over two or more fill or pick yarns and by advancing interlacing one pick with each warp. The sateen weave has even fewer pick interlacings than the twill weave, and these, spaced widely and regularly, provide a smooth surface with increased porosity, which makes them particularly valuable in dust collection. In equivalent construction, twill weave has fewer interlacings than the plain weave and, hence, greater porosity; but cotton sateen is probably used more commonly than any other fabric weaves in filters operated at ambient temperatures.

Felted fabrics--Because felted fabrics are complex, labyrinthine masses of randomly oriented fine fibers, whose relative thickness provides maximum dust impingement and changes of flow direction to entrap small dust and fume particles, the felted fabric filters operate with extremely high collection efficiencies.[116] Felted fabrics, used in reverse jet and pulse jet baghouses, have filtering velocities 5 to 6 times[106] those of woven fabric filters. Felted bags, more expensive than woven bags, are available in wool and such synthetics as Dacron, nylon, Nomex, polypropylene, and Teflon but not in cotton or fiberglass.

Principal considerations for selection of a felt for a particular process include:[117]

1. Fiber characteristics needed to meet chemical and thermal resistances.
2. Type of construction.
3. Physical properties of felt, such as density, breaking strength, elongation, bursting strength, air permeability, and particle size retention.

Felted bags do not function well in the collection of extremely fine fumes if fine particles embed in the felt; these are difficult to remove in the cleaning cycle. Generally, felted bags are cleaned by high-pressure reverse jet and jet pulse devices that operate at frequent intervals, and each bag in a unit is cleaned individually.[116]

4.6.3 Operational Factors

Fabrics applied in commercially available baghouses are shown in Table 4-15.[97,112,118] When comparing cost rankings given in Table 4-15, other factors also should be considered: use of a high temperature fabric reduces the amount of dilution cooling required[119] and requires less filtering area. For example, cooling gases from 477 to 394 K with ambient air at 305 K increases the final gas volume 60 percent; at 477 K, the filter requires only 62.5 percent as much cloth area as it does at 394 K. These reductions will lower power costs for operating the filter.[119]

Fabric materials rarely used are carbon, metals, and ceramic fibers that filter gases up to 1 144 K.[120] Beta fiberglass, a relatively new product, is more flexible and abrades less in service than regular fiberglass.[115]

Electrical characteristics can be important in fabric selection, since electrostatic attraction can reduce dust leakage. For example, agglomeration of negatively charged dusts may be aided by selection of a positively charged fabric.

Maintenance of a fabric filter is related to the original design; that is, high air-to-cloth ratios are often responsible for frequent bag replacements caused by fabric blinding or excessive bag wear. For conventional baghouses with woven fabric filters, the air-to-cloth ratios for each square meter are 0.0076 to 0.015 m^3/s for dusts and 0.0051 to 0.01 m^3/s for fumes; typical ratios and dust-conveying velocities for

Table 4-15. - FILTER FABRIC CHARACTERISTICS[97,112,118]

Fiber	Operating exposure, K		Supports com-bustion	Air perme-ability,[a] $m^3/s\text{-}m^2$	Composition	Resistance[b]				
	Long	Short				Abrasion	Mineral acids	Organic acids	Alkali	Cost rank[c]
Cotton	355	380	yes	0.5 -1.0	Cellulose	G	P	G	G	1
Wool	366	394	no	1.0 -3.1	Protein	G	F	F	P	7
Nylon[d]	366	394	yes	0.76-1.5	Polyamide	E	P	F	G	2
Orlon[d]	388	408	yes	1.0 -2.3	Polyacrylonitrile	G	G	G	F	3
Dacron[d]	408	438	yes	0.05-3.1	Polyester	E	G	G	G	4
Polypropylene	366	394	yes	0.04-1.5	Olefin	E	E	E	E	6
Nomex[d]	492	533	no	1.25-2.75	Polyamide	E	F	E	G	8
Fiberglass	560	588	yes	0.05-3.6	Glass	P-F	E	E	P	5
Teflon[d]	505	533	no	0.76-3.3	Polyfluoroethylene	F	E	E	E	9

[a] m^3/m^2 at 124.4 N/m^2.

[b] P = Poor, F = Fair, G = Good, E = Excellent.

[c] Cost rank: 1 = lowest cost, 9 = highest.

[d] Dupont registered trademark.

dusts and fumes collected in woven fabric bags are shown in Table 4-16.[121] Pressure drops range from 497.6 to 1 990 N/m^2. For reverse jet baghouses with felted or napped woven fabric filters, the air-to-cloth ratios for each square meter are 0.0508 to 0.081 m^3/s for dust and 0.0305 to 0.0508 m^3/s for fumes. Table 4-17 shows typical ratios for dusts and fumes collected in reverse jet baghouses.[122]

For woven bag filters, typical dust loading is 0.228 to 22.8 g/m^3 of gas; higher concentrations of particulates are sometimes removed by a precleaning device (e.g., a low-efficiency cyclone). For felted bag filters, maximum dust loading with reverse jet or pulse jet cleaning is 182.4 g/m^3. Figure 4-60 presents dust loading versus filter ratio data for various products.[123]

The more often a fabric, especially fiberglass, is cleaned, the shorter the bag life; this assumes that it is cleaned often enough to avoid fabric blinding by a dust overload. Fabric is normally cleaned when the pressure drop across the baghouse, or one of its compartments, increases 6 inches of water.[106] In large baghouses, the cleaning is scheduled by compartment, based on operating experience; but the cleaning may be scheduled to hold the pressure drop across a reverse jet baghouse with felted bags to 746.4 to 1 244 N/m^2.[124]

If dust is embedded and remains in the interstices of the cloth, normal cleaning does not completely remove it and it "blinds" or plugs the fabric pores to such an extent that the fabric resistance becomes permanently, excessively high. Once begun, blinding becomes worse rapidly. Collapse, a shift in cake structure, characterized by a more compacted condition and greater resistance, is caused by excessive filtering velocities. Variation in local filtering velocities, which has

Table 4-16. - RECOMMENDED MAXIMUM FILTERING RATIOS AND DUST-CONVEYING VELOCITIES FOR VARIOUS DUSTS AND FUMES IN CONVENTIONAL BAGHOUSES WITH WOVEN FABRICS[121]

Dust or fumes	Maximum filtering ratios, m^3/s-m^2 cloth area	Branch pipe velocity, m/s
Abrasives	0.051	23
Alumina	0.011	23
Aluminum oxide	0.010	23
Asbestos	0.014	18-20
Baking powder	0.013	20-23
Batch spouts for grains	0.015	20
Bauxite	0.013	23
Bronze powder	0.010	26
Brunswick clay	0.011	20-23
Buffing wheel operations	0.017	18-20
Carbon	0.010	20-23
Cement crushing and grinding	0.008	23
Cement kiln (wet process)	0.008	20-23
Ceramics	0.013	20-23
Charcoal	0.011	23
Chocolate	0.011	20
Chrome ore	0.013	26
Clay	0.011	20-23
Cleanser	0.011	20
Cocoa	0.011	20
Coke	0.011	20-23
Conveying	0.013	20
Cork	0.015	15-18
Cosmetics	0.010	20
Cotton	0.018	18
Feeds and grain	0.017	18
Feldspar	0.013	20-23
Fertilizer (bagging)	0.012	20
Fertilizer (cooler, dryer)	0.010	23
Flint	0.013	23
Flour	0.013	18

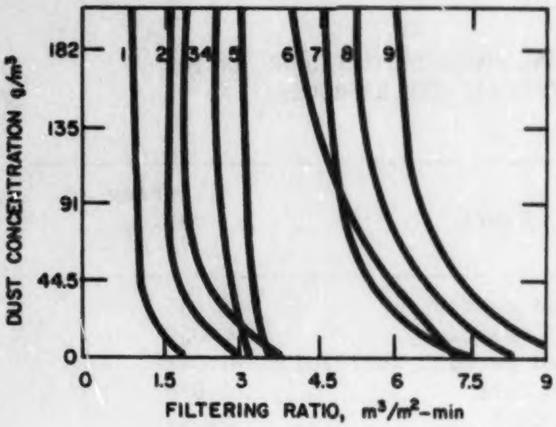
Table 4-16. - RECOMMENDED MAXIMUM FILTERING RATIOS AND DUST-CONVEYING VELOCITIES FOR VARIOUS DUSTS AND FUMES IN CONVENTIONAL BAGHOUSES WITH WOVEN FABRICS[121]

Dust or fumes	Maximum filtering ratios, $m^3/s-m^2$ cloth area	Branch pipe velocity m/s
Glass	0.013	20-23
Granite	0.013	23
Graphite	0.010	23
Grinding and separating	0.011	20
Gypsum	0.013	20
Iron ore	0.010	23-26
Iron oxide	0.010	23
Lampblack	0.010	23
Lead oxide	0.011	23
Leather	0.018	18
Lime	0.010	30
Limestone	0.014	34
Manganese	0.011	37
Marble	0.015	34
Mica	0.011	30
Oyster shell	0.015	34
Packing machines	0.014	30
Paint pigments	0.010	30
Paper	0.018	18
Plastics	0.013	34
Quartz	0.014	34
Rock	0.017	34
Sanding machines	0.017	34
Silica	0.014	34
Soap	0.011	18
Soapstone	0.011	30
Starch	0.011	18
Sugar	0.011	30
Talc	0.011	30
Tobacco	0.018	18
Wood	0.018	18

Table 4-17. - RECOMMENDED FABRICS AND MAXIMUM FILTERING RATIOS FOR DUST AND FUME COLLECTION IN REVERSE-JET BAGHOUSES[122]

Material or operation	Fabric	Filtering ratio, $m^3/s-m^2$
Aluminum oxide	Napped cotton	0.056
Bauxite	Cotton sateen	0.051
Carbon, calcines	Napped cotton, wool felt	0.041[a]
Carbon, green	Orlon felt	0.036
Carbon, banbury mixer	Wool felt	0.041
Cement, raw	Cotton sateen	0.046
Cement, finished	Cotton sateen	0.051
Cement, milling	Cotton sateen	0.041
Chrome, (ferro) rushing	Cotton sateen	0.051
Clay. freen	Cotton sateen	0.051
Clay, vitrified silicious	Cotton sateen	0.061
Enamel (porcelain)	Napped cotton	0.061
Flour	Cotton sateen	0.071[a]
Grain	Wool felt, cotton sateen	0.082
Graphite	Wool felt	0.036[a]
Gypsum	Cotton sateen, orlon felt	0.051
Lead oxide fume	Orlon felt, wool felt	0.041[a]
Lime	Napped cotton	0.051
Limestone (crushing	Cotton sateen	0.051
Metallurgical fumes	Orlon felt, wool felt	0.051[a]
Mica	Napped cotton	0.056
Paint pigments	Cotton sateen	0.051
Phenolic molding powders	Cotton sateen	0.051
Polyvinyl chloride (PVC)	Wool felt	0.051[a]
Refractory brick sizing (after firing)	Napped cotton	0.061
Sandblasting	Napped cotton, wool felt	0.031-0.041[a]
Silicon carbide	Cotton sateen	0.046-0.056
Soap and detergent powder	Dacron felt, orlon felt	0.061[a]
Soy bean	Cotton sateen	0.071
Starch	Cotton sateen	0.051
Sugar	Cotton sateen, wool felt	0.051[a]
Talc	Cotton sateen	0.056
Tantalum fluoride	Orlon felt	0.031[a]
Tobacco	Cotton sateen	0.061
Wood flour	Cotton sateen	0.051
Wood sawing operations	Cotton sateen	0.061
Zinc, metallic	Orlon felt, dacron felt	0.056
Zinc oxide	Orlon felt	0.041[a]
Zirconium oxide	Orlon felt	0.041

[a] Decrease 0.0051 $m^3/s-m^2$ if dust concentration is high or particle size is small.



KEY

1. MAGNESIUM TRISILICATE
2. CARBON BLACK
3. STARCH DUST
4. RESINOX
5. DIATOMACEOUS EARTH
6. KAOLIN
7. CEMENT OR LIMESTONE DUST
8. COAL DUST
9. LEATHER BUFFERING DUST

FOR NUMBERS 1 THROUGH 6, 99.94 - 99.99 PERCENT PASSING 325 MESH. FOR NUMBERS 7 AND 8, 95 PERCENT PASSING 200 MESH. NUMBER 9, 60 MESH AVERAGE.

Fig. 4-60. Typical performance of reverse-jet baghouse using felted fabrics on a variety of dusts (dust load versus filtering ratio at 871 N/m^2).

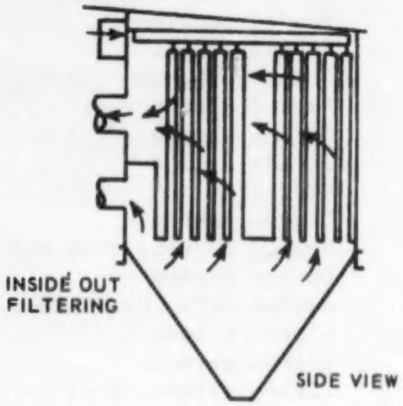


Fig. 4-61. Mechanical shaking of bottom entry design unibag dust collector.

exceeded a factor of 4 throughout a single filter bag, may lead to collapse or puncture of the filter cake.[125] Transient local filtering velocities of 0.51 m/s through areas of puncture have been observed when the average filtering velocity was only 0.0041 m/s. Punctures are usually self-repairing because the increased air flow brings more dust to the area of low resistance. Regularly, each bag must be inspected for holes or tears, and downstream dust concentrations should be measured manually or with an electronic eye to detect increases caused by leakage.[121] Leakage through the filter is perhaps the most important service problem. Bag spacing is important both to facilitate inspection and maintenance and to prevent one bag from rubbing another. A minimum clearance of 50 mm is needed between bags 3 to 4 m long;[106] and longer bags require greater clearances to avoid excessive wear.

Temperature in the baghouse should be 280 to 380 K higher than the dewpoint of the gas;[109] in some cases, insulated ductwork and baghouses maintain temperatures, and in others, a small auxiliary heater prevents condensation when a baghouse is shut down. To avoid plugging of felted fabrics caused by condensation when handling gases with high moisture content, preheated air may be necessary in reverse jet cleaning.[106]

Dimensional stability may be lost if the fabric is subjected to temperatures near those used in the original heat-setting process. Excessive temperatures can cause shrinkage of 3 or 4 percent, and shrinkage may cause a bag to pull loose from its connection to the floor plate or the upper support structure. Cottons and wools must be preshrunk. Synthetics are usually given a corresponding treatment known at "heat-setting"[106] for a more even balance of warp and filling yarn tension, virtual elimination of shrinkage, and control of porosity.

Porosity is decreased by precoating fabrics with asbestos floats or similar materials, to form an artificial filter cake that prevents dust leakage. Woven natural fabrics are treated with flameproofing, moldproofing, shrinkproofing, and/or dust-releasing coatings, such as silicone, to increase service life.[106] Woven synthetic fibers are treated with flameproofing and dust-releasing coatings. Fiberglass bags are treated with silicone, mixtures of silicone and colloidal graphite, and Teflon lubricants to protect against abrasion and flex failures caused by fiber-to-fiber rubbing;[117] these lubricants are effective at 311 to 590 K.

4.6.3.1 Fabric Filter Cleaning Methods--Among the usual techniques for fabric flexing are manual shaking, mechanical shaking, and air shaking. In manual shaking, used in baghouses of about 45 to 55 square meters of cloth, a rap transmitted to the framework from which the filtering bags are suspended vibrates the dust loose. Thorough cleaning is rare because the shaking depends on the operator's vigor.[106] This method is the least expensive but the least desirable.

Mechanical shaking (Fig. 4-61) used for inside-outside filtering to remove dust from woven fabrics is analogous to hand-shaking a rug.[113] The gentle but effective cleaning action exerts no undue stress on the fabric; however, it is ordinarily too vigorous for fiberglass bags.[109] The shaker design must permit easy installation, alignment, and maintenance.

Air shaking includes windwhipping, air bubbling, jet pulsing, reverse air flexing, and sonic vibration. Windwhipping (Fig. 4-62) cleans by flowing air between rows of bags;[125] bags are overcleaned near the orifice or jet and undercleaned in blind areas away from the action.

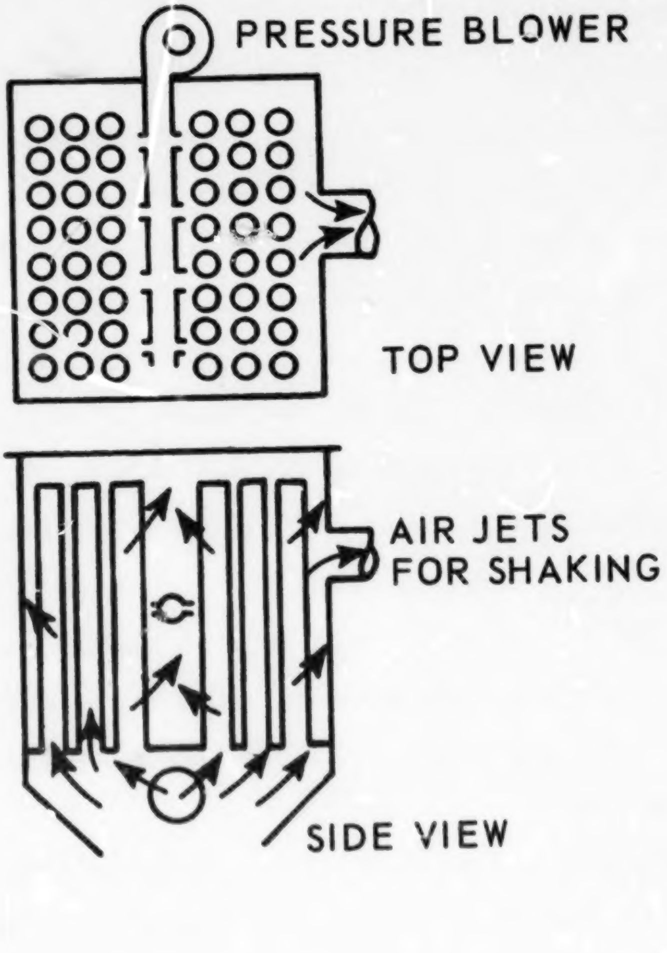

PRESSURE BLOWER
TOP VIEW
AIR JETS
FOR SHAKING
SIDE VIEW

Fig. 4-62. Air shaking wind-whip cleans dust collector bags.

This technique requires a minimum of hardware, but is usually too vigorous for fiberglass bags.[109]

In air bubbling (Fig. 4-63), a bubble released at the top of the bag travels downward and causes the bag to ripple. The compressed air requirements are high; cleaning at higher air-to-cloth ratios has not been proven. This technique is used for inside-out filtering and sometimes for fiberglass bags.[109]

In jet pulsing (Fig. 4-64), a jet of compressed air through a venturi section causes the bags to pulse outward, vibrates the fabric, and removes the dust. The dust is cleaned from the collection surfaces by a flicking action rather than by a reverse flow through the fabric. The jet pulse provides uniform pressure drop and continuous, automatic cleaning with no moving parts, and it permits high air-to-cloth ratios and thus requires small units for equivalent capacity. This technique, normally used with outside-in filtration with felt bags, has two disadvantages: the cost of a supporting frame and high replacement costs of felted fabrics.[109]

In reverse air flexing (Fig. 4-65), a double or triple cycle deflation of the bags is followed by gentle inflation through low-pressure reverse flow. The cloth cleaning is not exclusively by shaking; some backwashing occurs. This technique is used for inside-out filtering with fiberglass bags.

Occasionally, sonic generators (Fig. 4-66) are used for cleaning.[109] These vibrate the dust loose from the collecting fabrics. They are sometimes used to supplement repressuring and reverse flow cleaning. Some carbon black and zinc oxide installations use repressuring and sonic horns to clean fiberglass bags.[109]

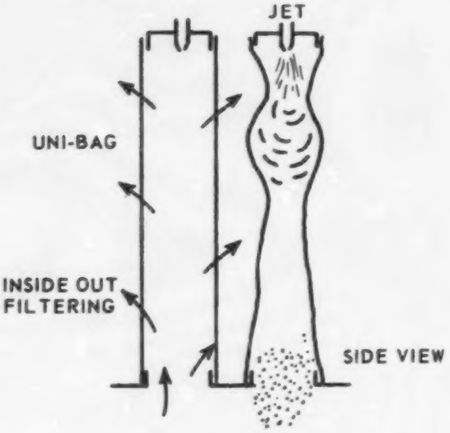

JET
UNI-BAG
INSIDE OUT
FILTERING
SIDE VIEW

Fig. 4-63. Bubble cleaning of dust collector bags.

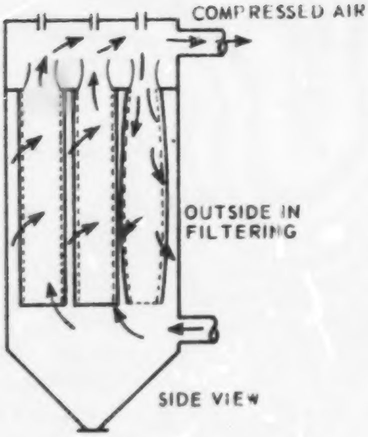
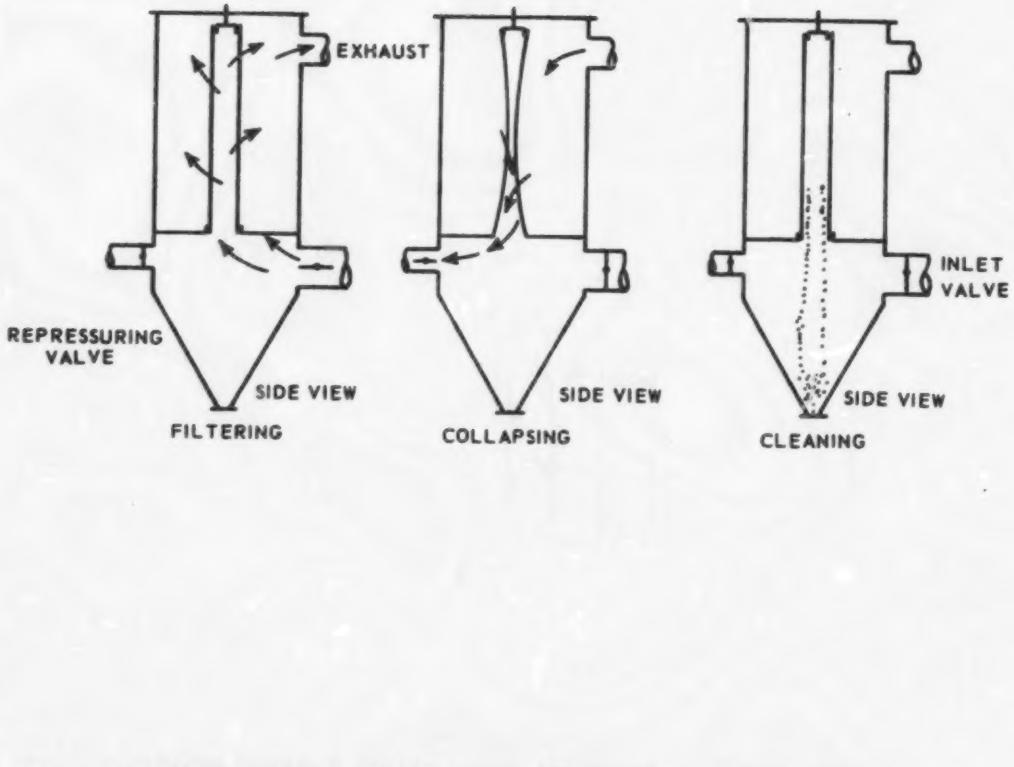

COMPRESSED AIR
OUTSIDE IN
FILTERING
SIDE VIEW

Fig. 4-64. Jet pulse dust collector bag cleaning.



EXHAUST
REPRESSURING VALVE
SIDE VIEW
FILTERING
SIDE VIEW
COLLAPSING
INLET VALVE
SIDE VIEW
CLEANING

Fig. 4-65. Reverse air flexing to clean dust collector bags by repressuring.

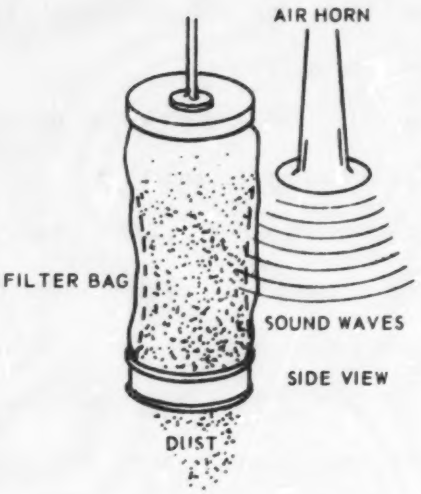

AIR HORN
FILTER BAG
SOUND WAVES
SIDE VIEW
DUST

Fig. 4-66. Sonic cleaning of dust collector bags.

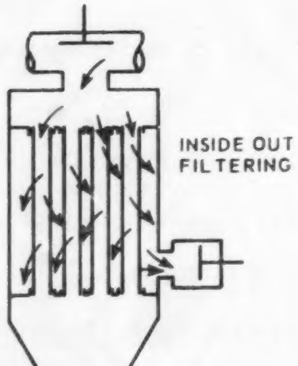

INSIDE OUT
FILTERING
SIDE VIEW

Fig. 4-67. Repressuring cleaning of dust collector bags.

Three reverse airflow techniques are repressuring cleaning, armospheric cleaning, and reverse jet cleaning.

Repressuring cleaning (Fig. 4-67) with a low pressure, high volume reverse airflow is used for woven or felted bags.

In atmospheric cleaning of closed suction baghouses, a vent in the damper opens when the compartment damper valve closes to the atmosphere and allows a backwash of air to clean the cloth (Fig. 4-68). This action is gentle and is used only with fiberglass cloth and easily removed dust. If the cloth resistance is high, the amount of backwash air is diminished and the cleaning action is less.[109] Sonic horns may be used to supplement the cleaning.

In reverse jet cleaning (Fig. 4-69), a traveling air ring of compressed air moves up and down the outside of a tubular filter bag and blows the dust back through the cloth and off the inside of the bag. The volume of air blown through 25 mm of the slot of the blow ring usually ranges from 0.00047 to 0.0007 m^3/s.[106] Slot widths range from 0.76 to 6.35 mm. Reentrainment of fine dust can cause high pressure drops across baghouses collecting fine fumes, but the technique is successful with felted bags with high air-to-cloth ratios collecting relatively coarse, nonabrasive dusts. The replacement cost of bags is somewhat high, but the unit is capable of a compact installation.[109]

4.6.3.2 Dust-Handling and Gas-Cooling Equipment--Collectors that must be regularly cleaned and reused require dust-handling equipment such as hoppers. Hoppers empty dust through a gate, a rotary lock, or a tricle valve into a screw (or belt) conveyor, a truck body, or a tote bin,[105] where it stays until it is conveyed to the final disposal point. Hoppers should be sized to hold the collected dust until it is removed for disposal.

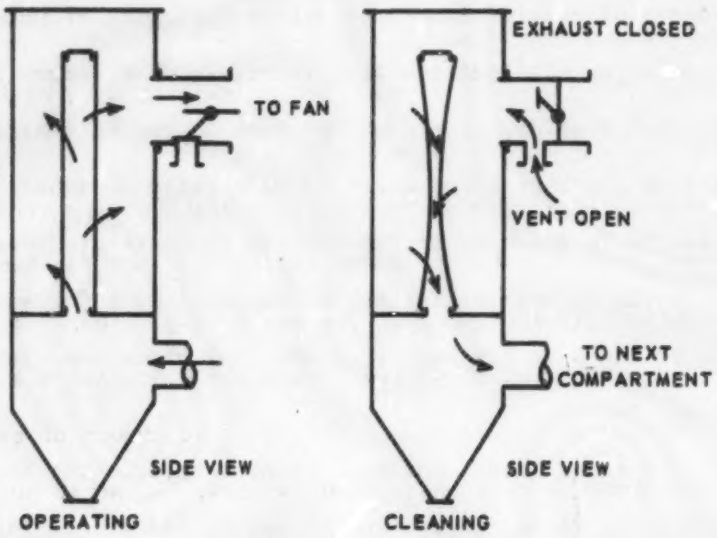

EXHAUST CLOSED
TO FAN
VENT OPEN
TO NEXT COMPARTMENT
SIDE VIEW
SIDE VIEW
OPERATING
CLEANING

Fig. 4-68. Cloth cleaning by reverse flow of ambient air.

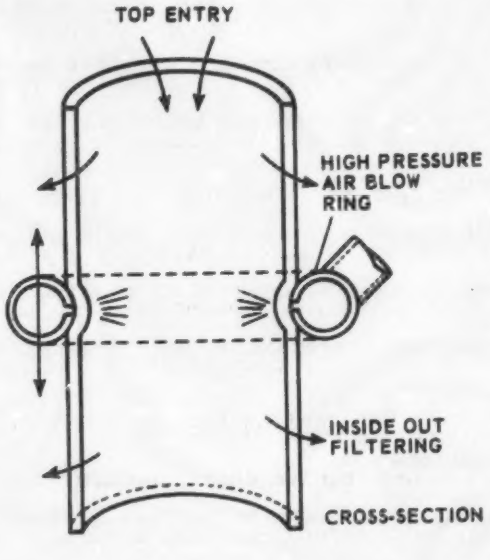

TOP ENTRY
HIGH PRESSURE AIR BLOW RING
INSIDE OUT FILTERING
CROSS-SECTION

Fig. 4-69. Reverse jet cleaning of dust collector bags.

The sides of the hopper must be steep enough for the dust to slide freely. Continuous removal of dust will help to prevent bridging of material and will prevent operating difficulties with materials that become less fluid with time. Careful consideration must be given to the dust-handling system at the time the fabric collector is originally designed.[105] Failure to do so may result in leakage, redispersal of the collected dust, and air pollution problems; inaccessibility of the equipment for servicing, or undersizing of the dust disposal equipment may block the upstream flow of process materials.

Cleaning of furnace gases requires, in most cases, that the gases be cooled to protect the filter fabric and to ensure bag life. Three cooling methods are used singly or in combinations:[126]

1. Radiation and convection cooling require a relatively large investment in U-tube coolers or heat exchangers.
2. Admission of outside air results in relatively large filtration volumes that require sizeable gas-cleaning equipment, but it is the best technique for avoiding condensation.
3. Spray cooling requires the lowest capital investment, but it requires careful control of cooling water sprays to prevent condensation and plugging of filters.

4.6.4 Typical Applications

The following examples illustrate typical uses of fabric filtration.

4.6.4.1 Cement Kilns--Collection of dust from rotary cement kilns has long been difficult because of the large volumes of gas, the heavy loading of very fine particles, the high gas temperatures, and in the case of wet-process kilns, the large amount of water vapor.[127] The conventional cyclone will collect a high percentage of the dust, but only the electrostatic precipitator and the fabric collector are capable of complete cleanup.[128-130] Efficiencies as high as 99.5 percent, outlet loadings below 45.6 mg/m^3, and plume opacities less than 10 percent have been reported for fabric filter applications to cement kilns.[129]

4.6.4.2 Foundary Cupolas--Fine metal oxides (less than 0.5 µm) from a gray iron cupola are prime examples of particulates that can be controlled with high temperature fabric filtration. Cupola exhaust ranges from 810 to 1 475 K and effluent loadings average about 2.28 g/m^3.[131] High temperature fabric filters and evaporation cooling by water sprays, the most common techniques used in gas cooling, are required. Off-gas temperatures are reduced to about 505 K before filtration through fiberglass bags. In a typical installation, the gas is filtered at about 0.013 $m^3/s\text{-}m^2$ through tubular bags that are 0.291 by 4.72 m. A bag life of 1 or 2 years can be expected if bags are used continuously; if noncontinuously, they average 20 to 40 hr/wk onstream and last 4 to 5 years.[131]

4.6.4.3 Electric Arc Steel Furnaces--The emission control problem for the electric arc steel furnace is characterized by fine particles (mostly oxides of iron) dispersed in a gas stream that is highly variable in temperature, loading, and volume during the different process cycles. Effluent volume depends on the hooding arrangement because the dilution air flow is adjusted for gas cooling and in-plant dust control. With closed hooded units, stack temperatures may reach 670 K or higher.[132]

The first large-scale fiberglass filter was installed in 1959 at a Seattle steel mill.[132] This unit handles 49.5 m^3/s up to 534 K by using fiberglass bags, 0.291 by 7.62 m, that operate at an air-to-cloth ratio of 0.007 m^3/s. The bags are cleaned by collapsing. Another example is a furnace melting 40 800 kg of steel scrap in 4 hours and using an Orlon fabric filter to handle a volume of 28.3 m^3/s at 367 K. The bag replacement cost is approximately $1 400 annually with a 5-year bag life.[132]

4.6.4.4 Open Hearth Furnaces--A major steel company found that iron oxide fumes generated by an oxygen-lanced open hearth furnace could be collected efficienctly by fiberglass bags.[133] The 10-compartment baghouse used in the study handles 68.4 m^3/s at 533 K, based on a filter ratio of 0.0102 $m^3/s\text{-}m^2$ when nine of the ten compartments are in operation. Each compartment contains 80 fiberglass bags, 0.291 by 10.36 m (or 752 square meters of filter surface per compartment). With reverse air flex cleaning supplemented by sonic horns, the efficiency of the baghouse is well over 99 percent under all conditions of inlet gas volume and dust loading. Inlet particulate loading has been as high as 45.6 g/m^3 during periodic cleaning of heat regenerative surfaces; outlet dust loading has been measured at 0.016 g/m^3.[134]

4.6.4.5 Nonferrous Metal Furnaces--To clean the combined effluent from a reverberatory furnace and a lead blast furnace, one of the largest secondary lead smelters in the country converted from synthetic fiber to fiberglass bags to permit fume collection at temperatures higher than 590 K. Higher temperatures were needed to eliminate the deposition of organic tars on the bags. After 16 months, fiberglass bags, operated at 0.006 $m^3/s\text{-}m^2$ and cleaned by shaking, are reportedly satisfactory.[131]

After pilot-scale studies of both synthetic and fiberglass media at an integrated smelter producing primary copper and zinc, a baghouse with 20 400 square meters of fiberglass bags was constructed to clean the effluent streams from a reverberatory furnace and copper converters.[131] Fiberglass was selected because it is corrosion resistant and because it reduces by 50 percent the radiation-convection heat transfer area required for cooling from 505 K to a temperature safe for organic media. The average filter rate is 0.0082 $m^3/s\text{-}m^2$. Bags are 0.127 by 3.05 m and are cleaned by collapsing every half hour and by mechanical shaking every 8 hours. An average bag life of over 2 years is anticipated.

4.6.4.6 Carbon Black Plants--Baghouses with fiberglass bags are reportedly used for the final cleaning in almost all carbon black plants in the United States.[135] Earlier, when synthetic bags were used, filtration was kept below 394 K to protect the media, and the evaporative cooling process brought the gas stream close to the acid dewpoint and caused serious fabric corrosion. The introduction of fiberglass in 1953 permitted operation at 477 to 533 K. Bag collapse, with some supplementary vibration from sonic horns or other gentle means, is the most common technique used for cleaning the fiberglass filters. Air-to-cloth ratios are usually 1.5:1. Average baghouse capacity is 23.6 m^3/s and bag life is 12 to 18 months.[135]

4.6.4.7 Grain Handling Operations--The important sources of grain dust emissions are cleaning, rolling, grinding, blending, and the loading of trucks, rail cars, and ships. Conveying and storing grains also cause dust emissions. For control, only low- and medium-efficiency cyclones are used because of the increased operating costs and maintenance problems of high-efficiency multiple cyclones. For dusts larger than 10 μm, a medium-efficiency cyclone is satisfactory; for dusts smaller than 10 μm, the fabric filter is preferred.[136]

Often, airstreams containing large amounts of dust are passed through a cyclone to reduce the volume of coarse particles to a fabric filter.

Receiving, handling, and storing operations require hooding and conveying of the dust-laden air to collection equipment. For receiving hoppers used in unloading rail cars and trucks, the air is exhausted from below the grating. The indraft velocity ranges from 0.51 to 1.53 m/s depending on whether the hopper is in a building or outside exposed to winds.

Fabric filters in the open or the closed pressure baghouse with mechanically shaken woven cotton bags reportedly remove 99.9 percent of 1- to 5-μm particles.[97] The air-to-cloth ratios are about 5:1. Reverse jet filters with felted fabrics reportedly remove 99.9 percent of particles 1 to 5 μm with air-to-cloth ratios as high as 15:1, although ratios of 12:1 are more common.[137]

4.7 AFTERBURNERS

Afterburners, which are used to dispose of fumes, vapors, odors, and low concentrations of combustible particulates from small volumes of gases, are of two types: direct flame burners and catalytic burners. For particulates, catalytic units are generally unsuitable. Consequently, the following discussion emphasizes direct flame units. In these units, disposal is limited to pollutants which are readily combustible and thus require short retention time in small furnaces.

When solids burn, the combustion zone is confined to the surface of the burning particle. At low temperatures, the combustion rate is limited by the chemical kinetics; at high temperatures, the reaction is so rapid that the rate of air supply controls the combustion.[138,139] In the zone surrounding the particle the temperature may exceed that of the particle surface and that of the surrounding gas by several hundred degrees. When liquid droplets and volatile solids are burned, the combustion zone is away from the surface of the particle and the combustion rate depends on the rate of heat transfer to the surface, which causes evaporation and thermal decomposition of the solid.

The transfer of heat from burner to gaseous and particulate matter is important in determining the furnace size, operating temperatures, and fuel requirements of direct flame contact incinerators. When gases are burned, heat transfer is best achieved by mixing; when particles are burned, the major mechanism is radiation from the incandescent surface of the particle.[140,141] Radiation and uniform furnace temperature may be achieved by mixing; when particles are burned, the major mechanism is radiation from the incandescent surface of the particle.[140,141] Radiation and uniform furnace temperature may be achieved by increasing the emissivity of the burner flame--that is, by limiting the air supply to produce a sooty flame, by using a fuel with a high carbon-to-hydrogen ratio, by adding soot or fuel oil to gas flames (carburetion), by using low-velocity burners, through poor mixing of air and fuel, and by altering furnace design.[142-144]

Most direct flame burners operated in the range of 923 to 1 090 K to produce maximum combustion within the limits imposed by flame contact, mixing, and retention time.[145] Figure 4-70 illustrates the effects of air velocity and particle size on the combustion rate of carbon.[146-148] The effects of particle size, reaction temperature, combustion gas composition, and gas velocity on the combustion rate of carbon, coal, and a number of other compounds have also been investigated.[138,139,149-153]

Preheat (induction) and combustion times dictate the overall retention time of the particulates in the afterburner; this time in turn determines furnace size and efficiency. Preheat time depends on the burner combustion intensity which varies from 37.3 kJ/s-m^3 for low-pressure gas jet mixers to

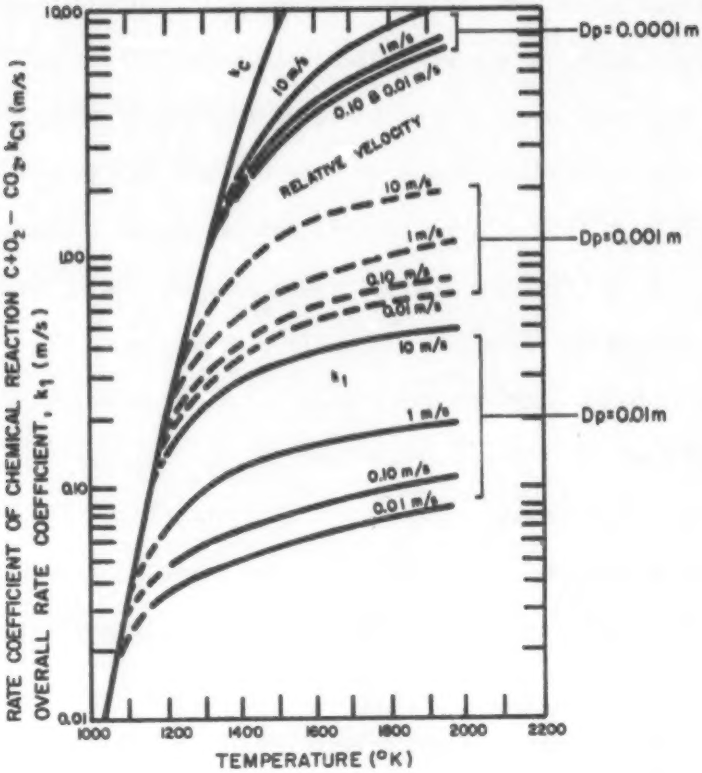


Fig. 4-70. Effect of air velocity and particle diameter on the combustion rate of carbon (D_p = particle diameter).

18.65 MJ/s-m^3 for premix mechanical burners. A typical value is 5.22 MJ/s-m^3 for premix, high-pressure, gas jet multiple-port burners; thus, the time required to heat a gas with a heat capacity of 1.22 kJ/m^3 from 366 to 1 255 K in a furnace with a combustion intensity of 5.22 MJ/s-m^3 would be 0.208 seconds. Combustion time depends on particle size and composition, on furnace temperature and oxygen supply, and on gas velocity and the mixing of combustibles. Combustion times for different materials have been correlated and are reported in the literature.[154]

In practice, minimum gas furnace retention time is about 0.30 second at 922 K. Particle retention time may be increased by designing the combustion chamber in the shape of a cyclone, using a small tangential inlet, and introducing the gases at a high velocity (Fig. 4-71).[145] Cyclone furnace dimensions are chosen using a gas velocity of from 15 to 9.2 m/s.[145,155] Good mixing is attained by using appropriate design parameters to provide turbulent flow in the afterburner.

The combustion constants for a number of organic compounds are presented in references 138, 139, 146-154, and 156-158.

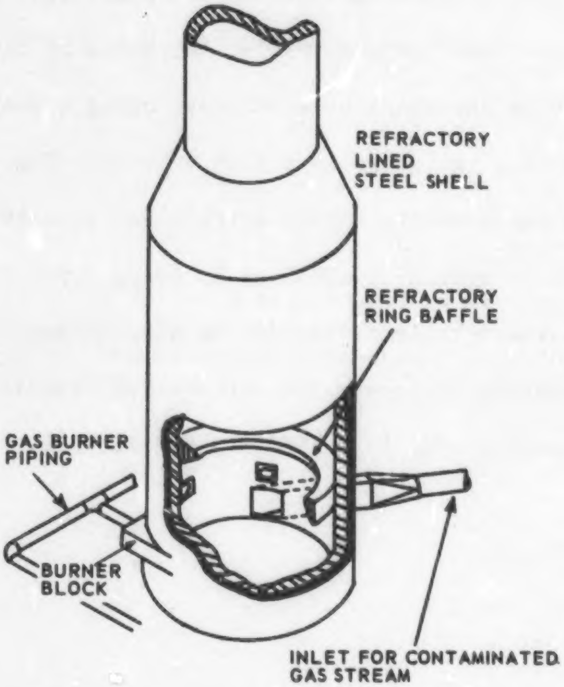

REFRACTORY LINED STEEL SHELL
REFRACTORY RING BAFFLE
GAS BURNER PIPING
BURNER BLOCK
INLET FOR CONTAMINATED GAS STREAM

Fig. 4-71. Typical direct-fired afterburner with tangential entries for both fuel and contaminated gases.

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5. EMISSION FACTORS FOR PARTICULATE SOURCES

An emission factor is a statistical average of the rate at which pollutants are emitted from the burning (or processing) of a given quantity of material. (The factors can be based on some other meaningful parameter, such as the number of miles traveled in a vehicle.) To determine each factor, reliable data from a source or group of sources are gathered, correlated with information on process use, and tabulated. Either an average or a range of values is selected.

Some emission factors are based on limited data; others, on extensive data that are highly variable; and still others, on extensive, consistent data. It is, therefore, important that the precision of the data be evaluated before the factor is used for estimating emissions.

In general, the emission factors for particulate air pollutants are not precise indicators for any single process even though the details of that process are known. They are more valid when applied to a number of processes.

Emission factors listed in Table 5-1 are for uncontrolled sources, except as noted in the table. Examples of how emission factors are used follow the table.

Table 5-1. - UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES[1]

Type of Emission Source		Emission Rate (g/kg)[1]
STATIONARY FUEL COMBUSTION SOURCE		
Bituminous Coal:		
Furnace greater than (30 MJ/s)		
General	(see note 2)	8.0
Wet bottom	(see note 2)	6.5
Dry bottom	(see note 2)	8.5
With cyclone	(see note 2)	1.0
Furnace from (3 to 30 MJ/s)		
Spreader stoker	(see note 2)	6.5
All others	(see note 2)	2.5
Furnace less than (3 MJ/s)		1.0
Hand-fired unit		10.0
Anthracite Coal:		
Dry bottom furnace	(see note 2)	8.5
Overfeed stoker	(see note 2)	1.0
Hand-fired unit		5.0
Fuel Oil:		
Power plant	kg/m^3	0.96
Industrial/commercial unit		
Residential	kg/m^3	2.76
Distillate	kg/m^3	1.8
Domestic unit	kg/m^3	1.2
Natural Gas:		
Power plant	kg/10^{6}m^3	256
Industrial process boiler	kg/10^{6}m^3	288
Domestic/commercial heating unit	kg/10^{6}m^3	304
Liquified Petroleum Gas (LPG):		
Industrial process furnace		
Butane	g/m^3	216
Propane	g/m^3	204
Domestic/commercial furnace		
Butane	g/m^3	228
Propane	g/m^3	216
Wood and Bark		12.5-15

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source		Emission Rate (g/kg)[1]
SOLID WASTE DISPOSAL		
Refuse Incinerator:		
Municipal multiple chamber		
Without settling chamber and water spray system		15.0
With settling chamber and water spray system		7.0
Industrial/commercial		
Multiple chamber		3.5
Single chamber		7.5
With control		0.7
Flue-fed		15.0
Modified flue-fed		3.0
Domestic single chamber		
Without primary burner		17.5
With primary burner		3.5
Pathological		4.0
Auto Body Incinerator:		
Without afterburner	kg/car 0.9	
With afterburner	kg/car 0.7	
Conical Burner:		
Municipal refuse		10.0
Wood (depending on burner adjustment)		0.5-10.0
Open Burning:		
Municipal refuse		8.0
Automobile components		50.0
Horticultural refuse		
Agricultural field burning		8.5
Landscape refuse and pruning		8.5
Wood		8.5
MOBILE COMBUSTION SOURCE		
Gasoline-Powered Motor Vehicles	kg/m^3 1.02	
Diesel:		
Truck or bus	kg/m^3 1.56	
Locomotive	kg/m^3 3.00	

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source		Emission Rate (g/kg)[1]
Aircraft:		
Turbofan		
Jumbo jet	kg/engine-LTO*	4.54
Long range	kg/engine-LTO	3.63
Medium range	kg/engine-LTO	3.18
Turbojet	kg/engine-LTO	4.99
Turboprop	kg/engine-LTO	2.72
Turboshaft	kg/engine-LTO	1.36
Piston		
Transport	kg/engine-LTO	2.27
Light	kg/engine-LTO	0.09
Vessel:		
Steamship		
Underway	kg/km	0.1
In-berth	kg/day	6.8
Motor ship		
Underway	kg/km	0.5
In-berth	kg/day	7.5
CHEMICAL PROCESS INDUSTRY		
Carbon Black Manufacture:		
Channel process		1 150
Thermal process		Neg
Gas or oil furnace (depending on degree of control)		5.0-110
Charcoal Manufacture (without chemical recovery)		200
Explosives Manufacture:		
Sulfuric acid regenerator		0.2
Red water incinerator		18.0
Hydrofluoric Acid Manufacture (grinding/drying of fluorspar)		10.0
Paint Manufacture	g/kg pigment	1.0
Phosphoric Acid Production (therman process):		
With packed tower		2.3
With venturi scrubber		2.8
With glass-fiber mist eliminator		1.5
With wire-mesh mist eliminator		1.4
With high-pressure-drop mist eliminator		0.1
With electrostatic precipitator		0.9

See footnotes at the end of the table.

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*LTO - Landing and Takeoff.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source			Emission Rate (g/kg)[1]
Plastics Manufacture:			
Polyvinyl chloride			17.5
Polypropylene			1.5
Others			2.5-5.0
Printing Ink Pigment Mixing			1.0
Spray Drying Detergents:			
Without control			45.0
With cyclone			7.0
With cyclone and spray chamber			3.5
With cyclone and packed scrubber			2.5
With cyclone and venturi scrubber			1.5
Soda Ash Conveying and Transferring			3.0
FOOD AND AGRICULTURAL INDUSTRY			
Alfalfa Drying:			
Without baghouse collector			30.0
With baghouse collector			1.5
Coffee Roasting:			
Direct-fired roaster			3.8
Indirect-fired roaster			2.1
Stoner and cooler			0.7
Instant coffee spray drier			0.7
Cotton Ginning:			
Unloading fan	kg/bale	2.3	
Cleaner	kg/bale	0.45	
Stick and bur machine	kg/bale	1.4	
Miscellaneous	kg/bale	1.4	
Grain Handling and Processing:			
Terminal elevator			
Shipping or receiving			0.5
Transferring, conveying, etc.			0.1
Screening and cleaning			2.5
Drying			3.0

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source	Emission Rate (g/kg)[1]
Country elevator	
Shipping or receiving	2.5
Transferring, conveying, etc.	1.5
Screening and cleaning	4.0
Drying	3.5
Corn meal processing	2.5
Soybean processing	3.5
Milo cleaning	0.2
Barley or wheat cleaning	0.1
Barley flour milling	1.5
Barley feed manufacturing	1.5
Fermentation:	
Beer	
Grain handling	1.5
Drying spent grain	2.5
Whiskey	
Grain handling	1.5
Drying spent grain	2.5
Wine	Neg
Fish Meal Drying	0.05
Meat Smoking:	
Without control	0.15
With control	0.05
Nitrate Fertilizer:	
Prilling tower	0.45
Dryer and cooler with prilling tower	6.0
Granulator	0.2
Dryer and cooler with granulator	3.5
Phosphate Fertilizer Manufacture:	
Normal superphosphate grinding and drying	4.5
Diammonium phosphate	
Dryer-cooler	40.0
Ammoniator-granulator	1.0
Starch Manufacture:	
Without control	4.0
With control	0.01

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source		Emission Rate (g/kg)[1]
Sugar Cane Processing:		
Field burning	g/m^2	25.2
Bagasse burning	g/m^2	12.0
METALLURGICAL INDUSTRY		
Aluminum Ore Reduction:		
Electrolytic cell		
Prebake		27.5
Horizontal stud soderberg		70.0
Vertical stud soderberg		40.0
Calcining aluminum hydroxide		10.0
Coke Manufacture:		
Byproduct coking		
Unloading		0.2
Charging		0.75
Coking		0.05
Discharge		0.3
Quenching		0.45
Behive oven		100
Primary Copper Smelting:		
Roasting		22.5
Smelting		10.0
Converting		30.0
Refining		5.0
Ferroalloy Smelting:		
Open electric furnace		
50% FeSi		100
75% FeSi		158
90% FeSi		282
Silicon metal		312
Siliconmanganese		98.0
Semicovered electric furnace--ferromanganese		22.5
Iron Production:		
Blast furnace		
Ore charge		55.0
Agglomerate charge		20.0
Sintering		
Windbox		10.0
Discharge		11.0

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source	Emission Rate (g/kg)[1]
Steel Production:	
Open-hearth furnace	
Oxygen lance	11.0
No oxygen lance	6.0
Basic oxygen furnace	23.0
Electric arc furnace	
Oxygen lance	5.5
No oxygen lance	3.5
Scarfing	10.0
Primary Lead Smelting:	
Crushing and sintering	25.0
Blast furnace	37.5
Reverberatory furnace	6.0
Primary Zinc Smelting:	
Roasting	60.0
Sintering	45.0
Horizontal retort	4.0
Vertical retort	50.0
Electrolytic process	1.5
Secondary Aluminum Smelting:	
Sweating furnace	7.25
Crucible furnace	0.95
Reverberatory furnace	2.15
Chlorination station . . . . . . g/kg chlorine used	500
Brass and Bronze Melting:	
Blast furnace	9.0
Crucible furnace	8.0
Cupola furnace	36.5
Electric induction furnace	1.0
Reverberatory furnace	35.0
Rotary furnace	30.0
Gray Iron Foundry:	
Cupola furnace	
Without control	8.5
With wet cap	4.0
With impingement scrubber	2.5
With high-energy scrubber	0.4
With electrostatic precipitator	0.3
With baghouse	0.1

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source	Emission Rate (g/kg)[1]
Reverberatory furnace	1.0
Electric induction furnace	0.75
Secondary Lead Smelting:	
Pot furnace	
Without control	0.4
With control	Neg
Reverberatory furnace	
Without control	65.0
With control	0.8
Blast (cupola) furnace	
Without control	95.0
With control	1.2
Rotary reverberatory furnace	
Without control	35.0
Magnesium Smelting:	
Pot furnace	
Without control	2.0
With control	0.2
Steel Foundry:	
Melting furnace	
Electric arc	6.5
Open-hearth	5.5
Open-hearth oxygen lanced	5.0
Electric induction	0.05
Secondary Zinc Smelting:	
Retort reduction furnace	23.5
Horizontal muffle furnace	22.5
Pot furnace	0.05
Kettle sweat furnace	
Clean metallic scrap	Neg
General metallic scrap	5.5
Residual scrap	12.5
Reverberatory sweat furnace	
Clean metallic scrap	Neg
General metallic scrap	6.5
Residual scrap	16.0
Galvanizing kettle	2.5
Calcining kiln	44.5

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source	Emission Rate (g/kg)[1]
MINERAL PRODUCTS INDUSTRY	
Asphalt Batching Plant:	
Rotary dryer	
Without control	17.5
With precleaner	2.5
With high-efficiency cyclone	0.4
With multiple centrifugal scrubber	0.1
With baffle spray tower	0.1
With ofifice-type scrubber	0.04
With baghouse	Neg
Other sources without control	5.0
Asphalt Roofing Manufacture:	
Asphalt blowing	1.25
Felt saturation	
Dipping	0.5
Spraying	1.5
Dipping and spraying	1.0
Brick Manufacture:	
Handling raw material	
Drying	35.0
Grinding	38.0
Storage	17.0
Curing and firing brick	
Gas-fired	Neg
Oil-fired	Neg
Coal-fired	2.5-5.0
Calcium Carbide Plant	
Electric furnace	
Hood	9.0
Main stack	10.0
Coke dryer	1.0
Furnace room vent	13.0
Castable Refractory Manufacture:	
Raw material dryer	
Without control	15.0
With baghouse	0.15
Raw material crushing and processing	
Without control	60.0
With scrubber	3.5
With cyclone	22.5

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source		Emission Rate (g/kg)[1]
Electric-arc melting		
Without control		25.0
With baghouse		0.4
With scrubber		5.0
Curing oven		0.1
Modling and shakeout		
Without control		12.5
With baghouse		0.15
Cement Manufacture:		
Dry process		
Kiln		121
Dryer, grinder, etc.		48
Wet process		
Kiln		100
Dryer, grinder, etc.		16
Ceramic Clay Manufacture:		
Drying		35.0
Grinding		38.0
Storage		17.0
Sintering:		
Fly ash		55.0
Clay mixed with coke		20.0
Natural clay		6.0
Thermal Coal Dryer:		
Fluidized bed		10.0
Flash		8.0
Multilouvered		12.5
Concrete Batching:		
Without control	kg/m^3 0.12	
With control	kg/m^3 0.012	
Fiberglass Manufacture:		
Reverberatory furnace		
With regenerative heat exchanger		1.5
With recuperative heat exchanger		0.5
Electric induction furnace		Neg
Forming line		25.0
Curing oven		3.5

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES--Continued

Type of Emission Source	[illegible]ssion Rate (g/kg)[1]
Frit Smelter Rotary Furnace	8.0
Soda-Lime Glass Melting	1.0
Gypsum Processing:	
Raw-material dryer	
Without control	20.0
With fabric filter	0.1
With cyclone and electrostatic precipitator	0.2
Primary grinder	
Without control	0.5
With fabric filter	0.0005
Calciner	
Without control	45.0
With fabric filter	0.05
Conveying	
Without control	0.35
With fabric filter	0.0005
Lime Manufacture:	
Crushing	
Primary	15.5
Secondary	1.0
Calcining	
Vertical kiln	4.0
Rotary kiln	100
Mineral Wool Processing:	
Cupola	11.0
Reverberatory furnace	2.5
Blow chamber	8.5
Curing oven	2.0
Cooler	1.0
Vertical Perlite Expansion Furnace	10.5
Phosphate Rock Processing:	
Drying	7.5
Grinding	10.0
Transfer and storage	1.0
Open storage pile	20.0

See footnotes at the end of the table.

UNCONTROLLED EMISSION RATES FOR PARTICULATE SOURCES—Continued

Type of Emission Source		Emission Rate (g/kg)[1]
Rock-Handling Process:		
Primary crushing		0.25
Secondary crushing and screening		0.75
Tertiary crushing and screening		3.0
Recrushing and screening		2.5
Fines mill		3.0
Screening, conveying, handling		1.0
Storage pile		5.0
PETROLEUM INDUSTRY		
Petroleum Refinery:		
Boiler and process heater		
Oil-fired	kg/m^3	2.397
Gas-fired	g/m^3	0.32
Fluid catalytic cracker (fresh feed)	g/m^3	174
Moving-bed catalytic cracker (fresh feed)	g/m^3	48
WOOD PROCESSING		
Sulfate Pulping:		
Recovery boiler and direct contact evaporator		
Without control		75.5
With electrostatic precipitator		7.5
With venturi scrubber		23.5
Smelt dissolving tank		1.0
Lime Kiln		
Without control		22.5
With scrubber		2.0
Fluidized-bed calciner		
Without control		36.0
With scrubber		0.35
Pulpboard Manufacture:		
Paperboard		Neg
Fiberboard		0.3

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[1] Units other than g/kg are given at the end of the entries immediately preceding numerical values for uncontrolled rates; when controlled rates are known, they are listed by type of control applied.

[2] For units that are not hand fired, the weight percentage of ash in coal should be multiplied by the factor given. If the factor is 8 and the ash content is 10 percent, the uncontrolled particulate emissions are 80 g/kg of coal.

EXAMPLE 1: PARTICULATE EMISSIONS FROM COAL COMBUSTION

Annually, a spreader stoker without fly ash reinjection burns 9 Mkg (process weight) of coal. The control efficiency is 85 percent, the ash content is 10 percent (expressed as 10 in the computation), and the emission factor is 6.5 g/kg (Table 5-1).

$$\text{Emissions} = (9 \text{ Mkg})(10)(6.5 \text{ g/kg})(1 - 0.85)$$

$$= 88\ 000 \text{ kg/yr.}$$

EXAMPLE 2: PARTICULATE EMISSIONS FROM SOLID WASTE DISPOSAL

Annually, a commercial multiple chamber incinerator burns 2 Mkg of refuse. The emission factor (Table 5-1) is 3.5 g/kg.

$$\text{Emissions} = (2 \text{ Mkg})(3.5 \text{ g/kg})$$

$$= 7\ 000 \text{ kg/yr.}$$

EXAMPLE 3: PARTICULATE EMISSIONS FROM SECONDARY METAL SMELTING

Annually, an electric induction brass furnace processes 20 Mkg. The system is equipped with a 99-percent efficient baghouse, and the emissions factor (Table 5-1) is 1 g/kg.

$$\text{Emissions} = (20 \text{ Mkg})(1 \text{ g/kg})(1 - 0.99)$$

$$= 200 \text{ kg/yr.}$$

REFERENCE

1. "Compilation of Air Pollutant Emission Factors." U.S. Dept. of Health, Education, and Welfare, Office of Air Programs, Research Triangle Park, N.C., AP-52, 1972.

*U.S. GOVERNMENT PRINTING OFFICE: 1973 546-311/94 1-3